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THE FUNCTION OF CONDENSING STEAM IN AEROSOL SCRUBBERS

P. J. Davis
J. Truitt

OAK RIDGE NATIONAL LABORATORY
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THE FUNCTION OF CONDENSING STEAM IN AEROSOL SCRUBBERS

R. J. Davis and J. Truitt

Work done for National Air Pollution Control Administration, Division of Process Control Engineering, 3914 Virginia Avenue, Cincinnati, Ohio. Project Officers: Ben Eusebio, Bruce Harris

MARCH 1971

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
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ABSTRACT

The general objective of this work is to provide information which would allow the design of a particle scrubber which would efficiently and cheaply remove very fine (0.2-2 micron) particles from polluted air streams. The basic concept is to grow these fine particles up to a size which can be readily separated in a cyclone or other inertial device. The tiny particles would first be grown by steam condensation, then further grown by turbulent agglomeration.

A literature study was made to show that the 0.2-2 micron particles do represent a critical air pollution problem area and to show that the scrubber concept is theoretically (and in terms of some existing data) reasonable.

Experiments were done in a simple, vertical pipe, water cooled condenser into the bottom of which aerosol plus steam was fed. The aerosol concentration and particle size distributions were measured with and without steam addition for a variety of aerosols and steam condensation rates. These experiments demonstrated that growth does occur, even at low water vapor supersaturation, with a variety of particle substances (including hydrophobic, hydrophillic and hygroscopic substances), with a variety of particle sizes, concentrations, and steam condensation rates. Two simple models of patterns of growth by condensation are suggested which are consistent with the observed removal efficiency results; with hydrophobic particles massive growth of a fraction of the particles occurs, with hydrophillic and hygroscopic particles equal growth of all particles occurs. Experiments demonstrated that the removal efficiency of the condenser increased sharply with aerosol velocity and at very high particle number concentration; these qualitatively verified that growth subsequent to condensation can readily occur due to turbulent (or velocity gradient) agglomeration.

Observed removal efficiencies were commonly greater than 90%; such efficiencies were observed with a steam consumption rate as low as 19 lbs per 1000 ft^3 of aerosol which corresponds (assuming steam costs $\$0.25/10^6$ Btu) to a cost of $\$0.0047/10^3 ft^3$ of scrubbed aerosol. The results suggest that the concept is valid and should be pursued.

I. Summary

This report contains a critical survey of the needs and capabilities of removing fine particles from polluted air streams and an account of an experimental program, in which particle growth and deposition due to condensing steam, was studied. From the critical survey, long term aspirations and specific short term experimental objectives were extracted which are clearly oriented toward an economic scrubber.

The long term aspirations are toward a device which will efficiently and inexpensively scrub fine particles from air. The immediate experimental objectives were to demonstrate that particles of various sizes and substances do undergo growth in condensing steam at low supersaturation, to discover details of growth and deposition mechanisms associated with steam condensation and to deduce as much as possible about the potential economy of steam condensation scrubbing.

In the critical survey (which is summarized in more detail in Section II-A) it is developed that a most important need is to remove particles in the size range 0.2-2 micron diameter because these particles are most apt to deposit in the human lung, are largely responsible for reduced atmospheric visibility and have the longest, atmospheric airborne lifetimes (Section II-B). Available cleaning devices, including wet and dry inertial devices and electrostatic precipitators but excluding bag filters, do not efficiently remove 0.2-2 micron particles (Section II-C).

It was shown that the deposition mechanisms associated with condensing steam would consume much more power than either electrostatic precipiation or inertial impaction. It was predicted that economic use of condensing steam can be accomplished with a system in which condensing steam is used to increase the size of fine particles to a size which undergoes further rapid growth by turbulent agglomeration and in which the final deposition is accomplished in an inertial separator (Section II-D). Examples were given which demonstrate that particle growth due to condensation has improved the removal efficiency of operating inertial separators (Section II-E).

Out of the critical survey, the specific objectives of an experimental program were extracted. These were (as noted above): to demonstrate particle growth in condensing steam, to discover growth and deposition mechanisms and deduce potential economy of steam condensation scrubbing (Section III).

Experiments were done in a simple, vertical pipe, water-cooled condenser (Section IV-A) into the bottom of which aerosol plus steam was fed. The aerosol concentrations and particle size distributions were measured (Section IV-C) with and without steam addition for a variety of aerosols (Section III-D) and steam condensation rates. The experiment was designed so that particles would be swept to the cold walls by the temperature gradient (i.e., via thermophoresis) and so that removal efficiency would depend on the amount of particle growth (Section IV-B). The experimental results (Section V, VI-A, and VII-A) demonstrated particle growth of many particle sizes and substances. Two simple models of patterns of growth by condensation were suggested (Section IV-B) which are entirely consistent with the results (Section VI-A); with hydrophobic particles massive growth of a fraction of the particles occurs; with hydrophillic and hygroscopic particles equal growth of all particles occurs. Data also suggested that with high particle number concentration, or with increased turbulence, significant additional growth occurred due to turbulent agglomeration. High (greater than 90%)removal efficiency was commonly observed.

Cost efficiencies were compared (Sections VI-B, VII-B). Operating inertial devices (which do not efficiently remove fine particles) consume about 1.2×10^{-4} to 1.2×10^{-3} $\$/10^3 ft^3$ of treated gas volume. Approximate theory indicates that steam condensation with optimum use of growth by turbulent agglomeration could efficiently remove fine particles at a cost of 2×10^{-5} to 6×10^{-5} $\$/10^3 ft^3$. Our experimental system achieved high removal efficiencies with a power consumption cost of 4.7×10^{-3} to 1.1×10^{-2} $\$/10^3 ft^3$.

It is predicted that the cost efficiency of a steam condensation scrubber would depend significantly on optimum use of particle growth by turbulent agglomeration and that removal efficiency would depend significantly on water vapor supersaturation. Turbulent growth and the effect of supersaturation should be the subject of future study (Sections VII-C, VIII-B). Additional experiments of the present kind were also recommended (Section VIII-A) to determine the effects of number concentration, initial particle size and particle substance on particle growth more quantitatively than the presented data have done.

II. A Survey of the Needs and Capabilities of Removing Fine Particulate Air Pollution

A. Introductory Summary

In these first paragraphs the introductory arguments are outlined. These are the arguments that there is an important problem without adequate solutions and that there is a reasonable expectation that a solution has been conceived. In subsequent sections of the introduction, each of the arguments is explored in more detail.

There is a need for a cheap method of efficiently removing small particles from gaseous industrial effluents. The need is particularly for the removal of particles in the size range about 0.2 to 2 microns diameter. The reasons that the fine particles are most important are: these fine particles are most apt to deposit in the human lung; these small particles are largely responsible for reduced visibility through urban air; and these tiny particles also have the longest airborne lifetime because they neither agglomerate nor settle very rapidly.

The need is to remove the 0.2 to 2 micron diameter particles but the available air cleaning devices - excepting filters - remove these particles very inefficiently. Bag filters appear to be a sufficiently cheap solution to some air cleaning problems but are apparently too expensive for many applications. In common wet scrubbers as well as in dry centrifugal devices particles are accelerated toward a surface; the acceleration is accomplished by various means in devices such as cyclonic sprays, orifice and pipelines, Venturies, mechanical sprays and hydraulic nozzles. Correlation of removal efficiencies of such devices strongly indicate that the removal efficiencies depend only on the nature of the aerosol (probably particle size) and the power consumed to accelerate the particles. In other words, these correlations suggest that greater efficiencies with conventional inertial deposition devices would increase costs considerably, that efficient and cheap removal of tiny particles will require a deposition mechanism other than inertial impaction.

The deposition mechanisms associated with condensing steam may offer some useful solution to the problem of removing fine particles. This report is, indeed, an exploratory study of these mechanisms. The phrase, condensing steam, refers to the situation in which water is condensing from the aerosol and depositing onto a cold surface. The possible functions of condensing steam are fourfold. If the steam condenses directly onto the cold surface then it can be shown that the particles will drift in the water molecule concentration gradient toward the condensing surface. If the steam condenses onto the particles, the latent heat of condensation heats the aerosol and this heat will be conducted (probably across a stagnant layer) to the cold surface. Again it can be shown that particles will drift in the thermal gradient toward the cold surface. In the latter case, the particles will have become larger due to condensation of water onto them; there may be (if the experiment or scrubber is properly designed) one or both of two consequences of this particle growth. The grown particles may undergo further growth due to turbulent agglomeration (agglomeration by turbulence is predicted to occur at rates proportional to the cube of the particle diameter, hence larger particles are much more subject to growth in a turbulent medium.) The other possible consequence of growth is inexpensive removal by inertial impaction, i.e., the grown particles may more easily (and cheaply) be deposited in a cyclone or other inertial device. This latter consequence is of most practical importance.

The drift velocities (or deposition velocities) of particles in either a water molecule concentration gradient or in a temperature gradient can be estimated from available theories. Experiments have been done which confirm the theories adequately for the present purposes. It follows therefore that we can, with considerable confidence, calculate deposition velocities (and hence collection efficiencies of well defined devices) due to water molecule concentration gradients (i.e., due to diffusiophoresis) or due to thermal gradients (i.e., due to thermophoresis). We cannot confidently predict which will occur, i.e., whether the water will condense on cold walls (and cause diffusiophoresis) or condense on particles (and cause thermophoresis and particle growth). The uncertainties about growth due to condensation of water relate to uncertainties about where the water condenses; does it condense on walls and not on particles? Does it condense on a fraction of the particles? Does it condense equally on all particles? The rate of growth by turbulent agglomeration has been estimated theoretically (as a function of energy dissipated per unit volume of aerosol); but the theory has not been clearly demonstrated. It is not clear that turbulent growth can be confidently predicted. If growth could be estimated then the effect of growth on inertial deposition could be readily and confidently estimated (simply on the basis of the well established Stokes' law which evaluates the velocity of a particle in a gravitational field as a function of the particle size). To reiterate, the uncertainties about particle removal by steam condensation from a basic science point of view, are with regard to two questions: Where does the steam condense? How much growth occurs due to turbulent agglomeration?

Some actual scrubbers enjoy, to some extent, the help of these steam condensation sweep mechanisms and particle growth by steam condensation; others probably suffer hindrance from these same mechanisms. In a Venturi scrubber, for instance, if the aerosol is saturated in the pressure zone in the Venturi throat, the subsequent expansion (which is sudden and therefore approximately adiabatic), which removes work from the aerosol, will cool it and cause condensation to occur. It has been suggested that the water tends to condense on the particles and the grown particles are more readily collected by impaction with the water drop spray because they are larger. The sweep mechanisms may also cause the particles to move toward the water drops (i.e., if the water drops are colder than the gas). Conversely if the aerosol goes into the Venturi dry there can be no particle growth by condensation and furthermore the spray drops will tend to evaporate which will cause particles to drift away from the spray drops (i.e., diffusiophoresis and thermophoresis would be working against deposition of particles onto water drops). Experience has in fact shown that wet scrubbers are more efficient the colder the water and the higher the steam concentration in the aerosol; in other words, the more steam condensation onto the collecting surface, the higher the removal efficiency.

B. Three Reasons Why It is Most Important to Remove the Very Fine Particulate Air Pollution

The objective here is to show three reasons why very small particles are a particularly objectionable part of air pollution and therefore that devices to economically remove these small particles are critically needed. First, the small particles (about 1 micron diameter) are most apt to penetrate the particle trapping devices in the human breathing system and to reach the lungs; they can carry adsorbed aggressive chemicals, they stay in the lungs a long time and can do damage. Second, the small particles are almost wholly responsible for the reduction of visibility through polluted air. Third, the very small particles stay aloft for a long time. Each reason will be discussed in turn; the suggested conclusions are that the small particles are most objectionable and there is a critical need for devices to remove them.

The breathing system has efficient mechanisms for removing chemically aggressive molecules and large particles[1] to protect the lungs. These pollutants are rinsed into the stomach, and from there they proceed quickly through the relatively hardy digestive system. In contrast, small particles have been shown[2] to efficiently penetrate the bodily barriers and to reach the lungs where they stay for an extended period. These small particles have high specific surface area and may carry adsorbed molecules[1] of chemically aggressive substances (such as SO_2) which would not have been able to reach the lungs in the gaseous state. The percent of inhaled dust which reaches the lungs at different respiration rates is shown in Fig. 1 as a function of particle size.[2] The lung deposition efficiency also depends on particle density; we have chosen a density of 5.2 g/cm^3 to represent iron oxide particles (for example, from an electric arc furnace). The most efficiently deposited particle size range is about 0.2-2 micron diameter. This is apparently the size range which should be removed from the urban atmosphere with the most care if human health is to be the criteria.

Secondly, we will consider a second aspect of air pollution, that of reduction of visibility. Light has difficulty in traveling through an aerosol, the particles tend to scatter or to absorb the light. The details of light scattering and absorption are complex[3] but approximately the effect is proportional to the total cross sectional area of all the particles. A given mass of particle material will present a larger cross section of it is finely divided. Hence, the smaller the particle size, the greater the light scattering and absorption and the shorter the distance of visibility.

A useful quantitative definition of visibility or meteorological range[4] is the distance at which the contrast is 2%. With this definition, the formulation relating visibility to particle diameter, mass concentration, particle density, and Ke (a factor which depends on the wavelength of the light, particle substance and size) has been described.[3] The values of Ke for iron spheres are also available.[3]

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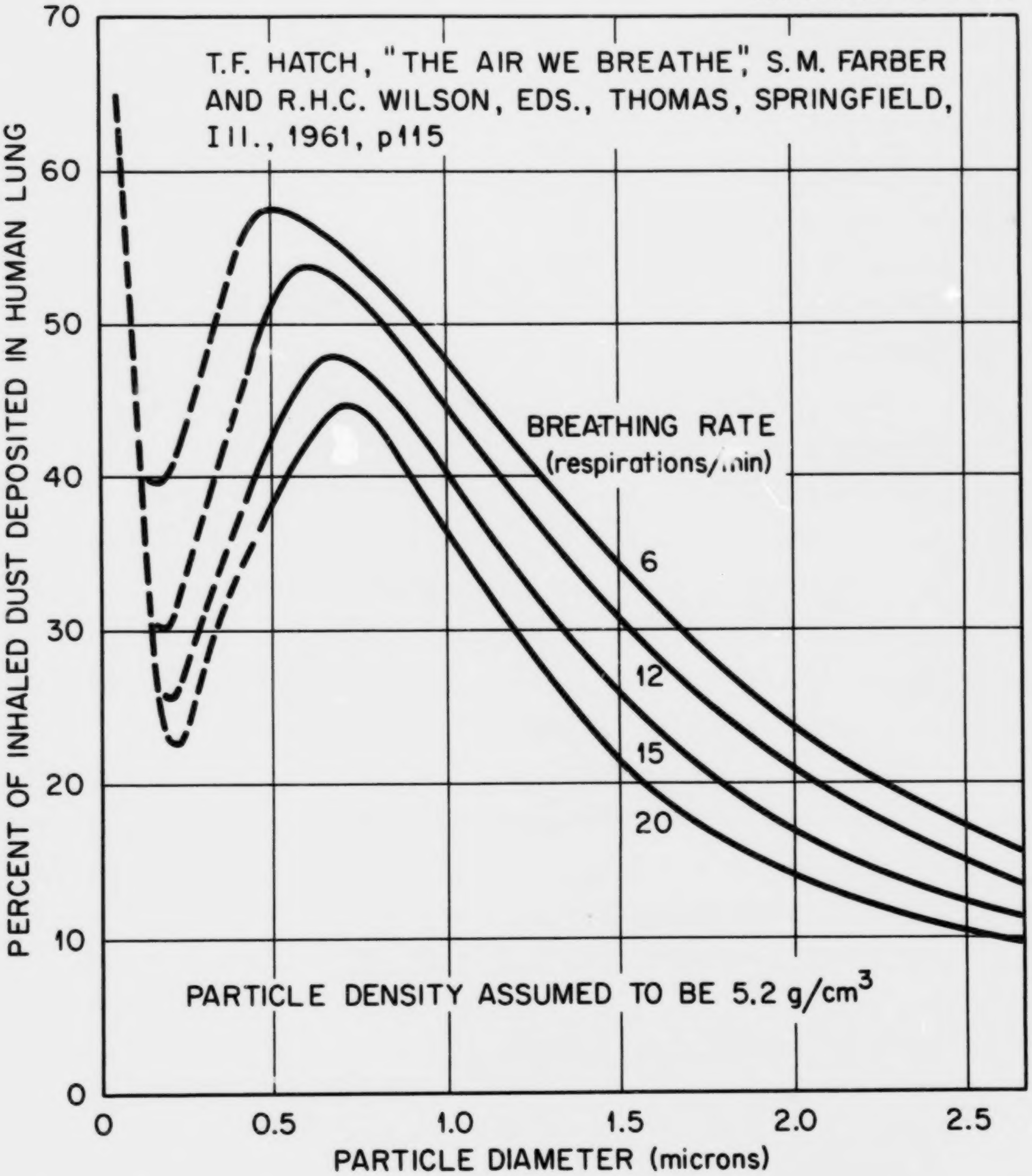

Figure 1. Relation Between Efficiency of Deposition in the Lung and Particle Size.

Figure 2 is a plot of calculated visibility in miles, of light of wavelength 6000 A° through an aerosol of monodispersed iron spheres containing 0.015g of particles per cubic meter vs the diameter of the spherical particles. The particular mass concentration was chosen because this value has been suggested as the maximum concentration to be allowed on the basis of public health.[5] As you can see from Fig. 2, this concentration would allow a considerable visibility so long as the particle diameter is rather large (say greater than 1 mile if the particle diameter is greater than 2.5 microns). On the other hand, 0.015 g/m^3 of about 0.3-micron particles would allow a visibility of only about 150 yards.

It is clear that if visibility is the measure of air pollution, then it is again most important to remove the small particles. The particle size range 0.2 to 2 micron diameter is particularly bad in regard to visibility limitation.

So both in terms of heatlh (the little particles deposit in the lung) and in terms of visibility, the small particles (particularly in the range 0.2-2 micron diameter) are the most serious. In addition, these small particles have a long airborne life time, that is, they are available for a long time to do their damage. The dependence of fallout rate on particle size is the third point to be made.

First, we need to consider particle size distribution because fallout rates depend on size distribution. Figure 3 is a plot of the normalized mass concentration distribution function[7] vs particle diameter for aerosols emitted from electric arc furnaces.[6] The data points approximately fit the lines on Fig. 3; in other words, the size distribution fits the expression:

$$[1/M]dM/dD = [1/\ln D_{max}/D_{min}]/D, \qquad (1)$$

where M is the mass concentration, D the particle diameter and D_{max} and D_{min} the maximum and minimum particle diameters. Many aerosols,[7] including urban and rural atmospheric aerosols[8], also fit this function. The data indicate that D_{max} was about 100 microns. The value of D_{min} is uncertain because the size distribution data did not go down to small enough particle sizes. The two sets of lines on Fig. 3 are based on two assumed values of D_{min}; one being 0.1 micron, the other 1 micron. Some of our results with metal oxide aerosols generated in electric sparks suggest that D_{min} for agglomerated, condensation aerosols (i.e., aerosols

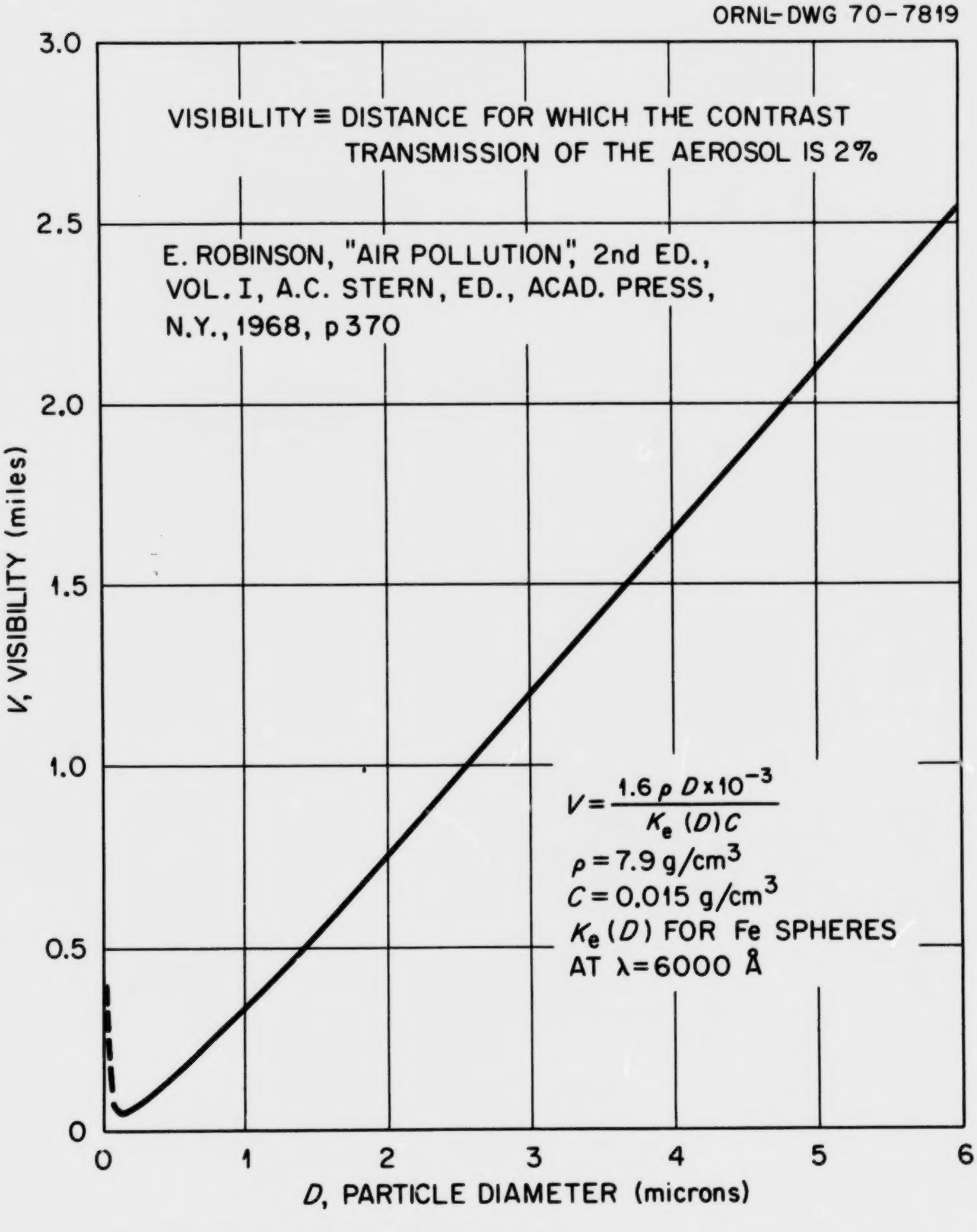

Figure 2. Estimated Visibility Through an Aerosol vs Particle Size.

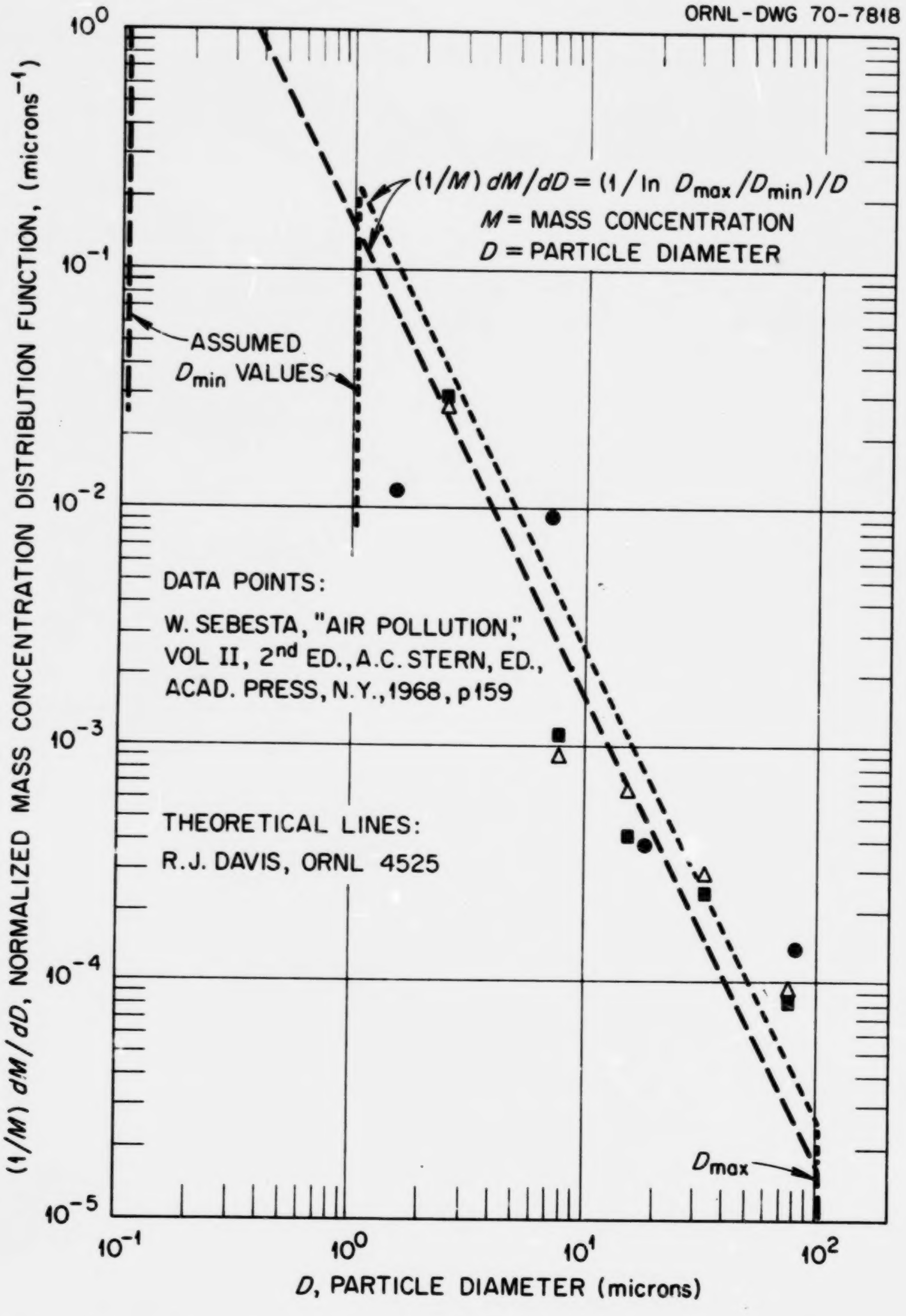

Figure 3. Distribution of Mass Concentration Among Particle Sizes for Emissions from Electric Arc Furnaces.

of particles initially formed by condensation from a concentrated vapor) of metal oxides can be as small as 0.01 micron. Figure 4 is a picture of such particles and illustrates the range of sizes including the minimum diameter of about 0.01 micron.

So it appears that the distribution function (i.e., Equation (1) and the slope of the lines on Fig. 3) is a reasonable representation of practical aerosols[6-8], that D_{max} of 100 microns is reasonable[6] and that D_{min} may be varied depending on the minimum size which industrial gas cleanup systems allow to be emitted into the atmosphere. We will therefore calculate a measure of the life-time of such an agglomerated aerosol as a function of D_{min}.

A calculation of fallout rates of aerosols with steady-state size distributions of the form shown in Eq. (1), has been developed.[9] This calculation accounts for particle growth by coagulation and deposition by gravitational settling. The calculation was originally developed for estimating aerosol concentration in a well-mixed, definitely defined volume. For the present purpose we presumed the polluted atmosphere to extend 500 feet high (which is in approximate agreement with observation).[10] It was presumed that aerosol particles were continuously formed and that a steady-state concentration was achieved in which the rate of smoke generation was equal to the rate of dust fall. The calculation was done for a dust fall rate of 100 tons/square mile/30 days which is a high dust fall rate for industrial areas).[11] We calculated the steady-state airborne concentration for a series of assumed values of D_{min} in the range 0.01 to 10 microns.

Figure 5 shows the results. It shows that the highest steady-state concentration would occur with minimum particle diameters in the range 0.2-2 microns. A qualitative explanation of the shape of the curves on Fig. 5 is in order. In general, if the minimum particle size is rather large (say > 2 microns) then all the particles fall out at a significant rate and the resulting steady-state airborne concentration is low. If the minimum particle size is very small (say < 0.2 micron) then the number concentration is necessarily very high, coagulation is therefore very rapid, and the rate of formation of very large (> 100 microns) particles which fall out very quickly is high. In other words, the steady-state concentration is controlled, in this case, by coagulation. The in-between particle sizes (0.2-2 microns)

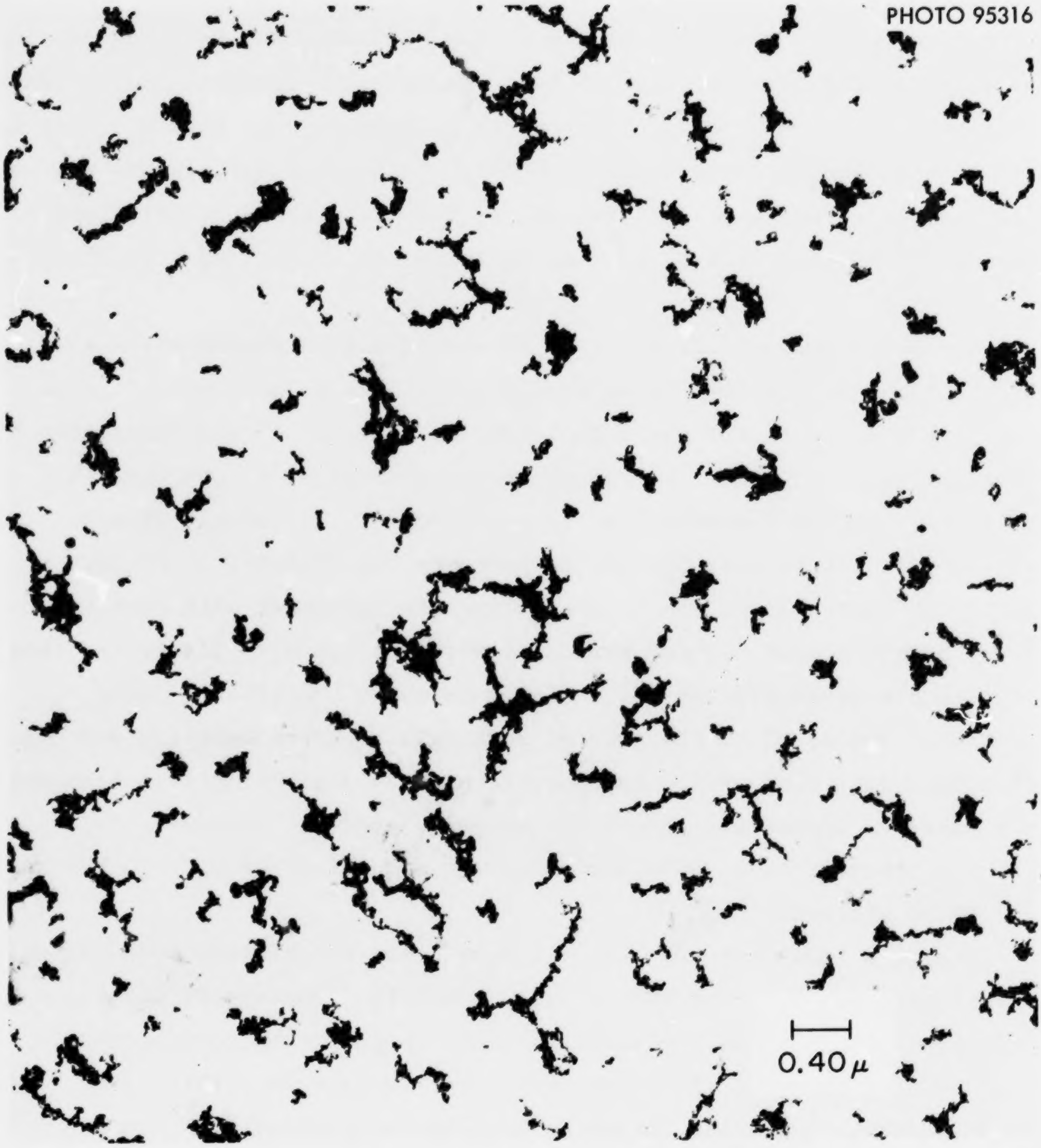
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Figure 4. Dry Stainless Steel Oxide Aerosol.

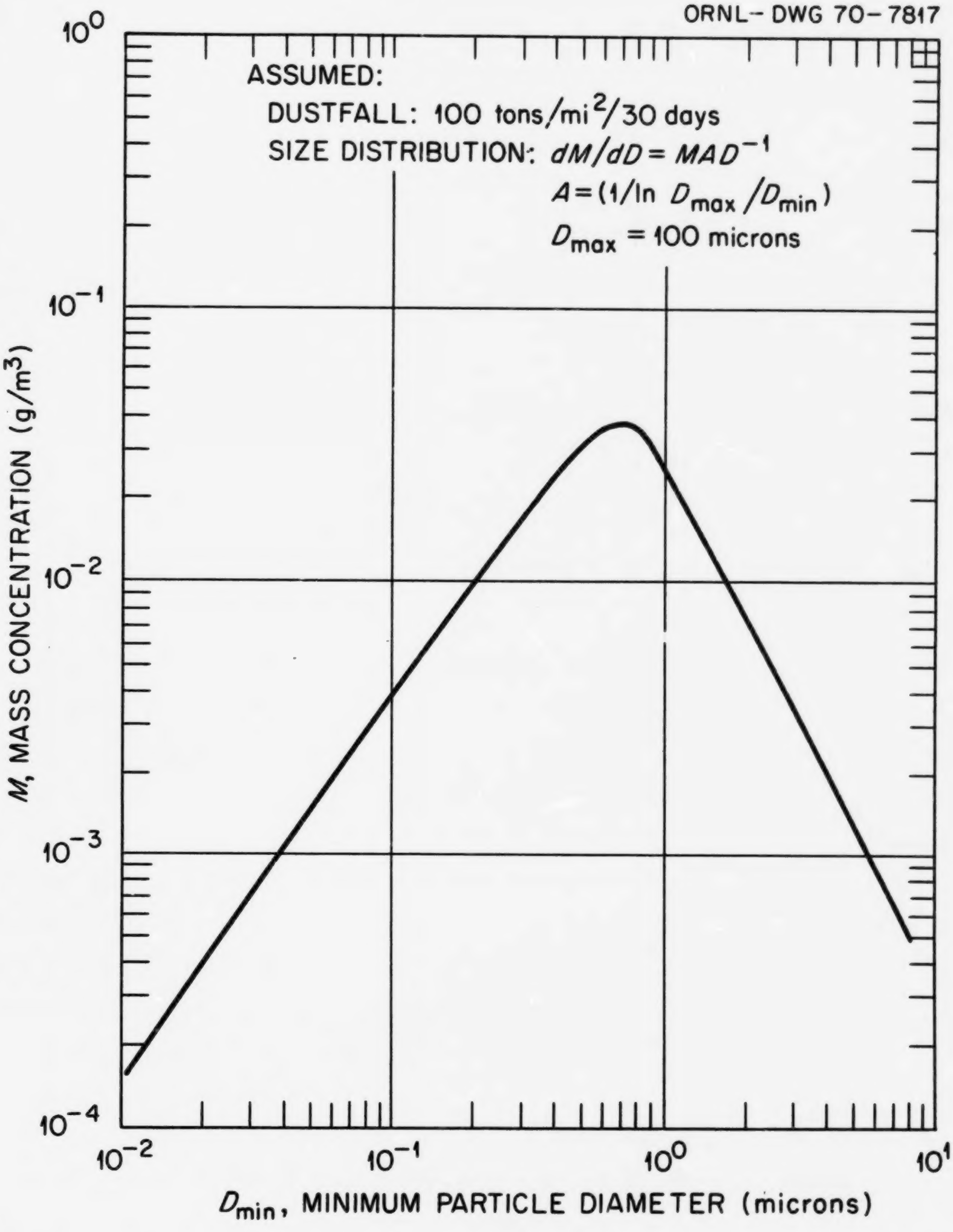

Figure 5. Steady State Aerosol Mass Concentration vs Minimum Particle Size.

neither coagulate rapidly nor settle rapidly; they form the most stable aerosols.

So in summary, the particle size range (perhaps roughly 0.2-2 micron diameter) constitutes the worst of particulate air pollution. These are the particles that get deposited in the lungs; these are the particles that cause reduced visibility; these are the particles that settle slowly and have a long airborne lifetime. Indeed, it appears that particulate air pollution could well be defined as the 0.2-2 micron particles.

It seems reasonable therefore that work to develop systems which can remove these small particles from industrial emissions be given an appropriate premium.

C. A Survey of Available Means to Remove Micron Size Particles from Industrial Effluents

The objective in the following paragraphs is to show the approximate collection efficiency of available systems for particles in the size (diameter) range 0.2-2 microns. This size range probably constitutes the greatest health hazard, is largely responsible for reduced visibility and leads to the most stable (longest lasting) atmospheric aerosols. We wish to see if available cleaning systems remove this size range of particles efficiently.

Figure 6 is a plot of collection efficiency (%) vs particle diameter (microns) for several types of filters. There are two basically different kinds of filters shown. The fibrous mat is one kind, the bag filter is the other. The collection efficiencies of many fibrous mats were reported by Whitby[12]; they depend largely on the fiber diameter[7] and almost any desired collection efficiency is possible, for the particles in the 0.2-2 micron range. Very large fibers (like the coarse polyurethane foam and aluminum) result in low collection efficiencies (for small particles) but fine fibers such as 0.1 micron fibers in glass cloth filters yield quite high collection efficiencies. Absolute filters are also available[13] which collect this particle size range of interest (0.2-2 micron) with an efficiency of 99.97%.

So fibrous filters are available which can achieve almost any collection efficiency desired. These filters, particularly the fine fiber filters, are expensive and cannot be readily cleaned; they are therefore probably not adaptable to wide scale use in cleaning industrial effluents.

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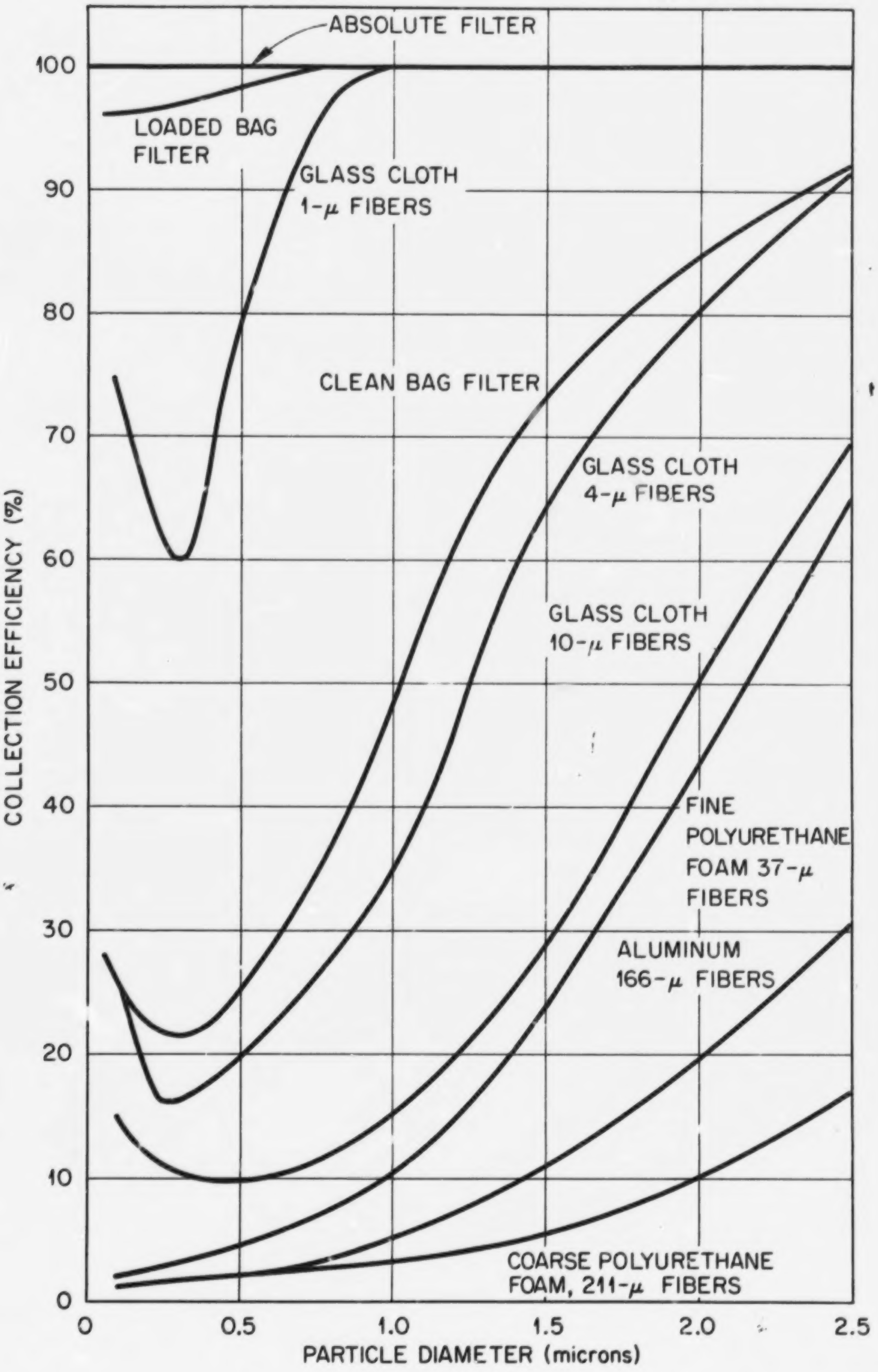

Figure 6. Particle Collection Efficiency of Filters.

Bag filter performance has been reported as a function of particle size.[14] In a bag filter a cake of the dust being filtered is allowed to build up and the filtration action is performed by the particles of dust. During the period of buildup of the cake, therefore the collection efficiency is relatively low; hence the two curves on Fig. 6, one for a clean bag filter and one for a loaded bag filter. Bag filter collection efficiencies can be very high, for the 0.2-2 micron particle size (as shown on Fig. 6). Bag filters do have some limitations in regard to temperatures of operation and maintenance costs.

Figure 7 outlines the efficiencies found[15] with devices such as cyclones and settling chambers which use the inertia of the particles to separate them from the gaseous medium. The results shown here are all for dry systems (i.e., systems in which no water is used).

The settling chamber and the louvered type (impaction) separator were very ineffective in removing 0.2-2 micron particles. The high efficiency (and low throughput) cyclones achieved significant, but still rather low, collection efficiencies for particles in the size range (0.2-2 micron) of interest. The best collection efficiency indicated on Fig. 7 for 1 micron particles is about 30%. It appears therefore that cyclone separators, even those of high efficiency design (which generally means low throughput, higher pressure drops and higher costs) are not very effective in collecting 0.2-2 micron particles.

Figure 8 shows some results for some types of available wet scrubbers. The gravity spray[15] (in which drops of water fall through the aerosol due to gravity) is almost totally ineffective for 0.2-2 micron particles. A centrifugal spray (in which drops of water are flung through the aerosol by a centrifugal force corresponding to 100 g) is considerably better; but still not very good. It achieves about 30% removal efficiency for 1 micron particles. The collection efficiency of Venturi scrubbers,[16] in which the aerosol is violently mixed with spray depends strongly on the amount of water fed into the system. At a high water feed rate the Venturi does as well as the centrifugal spray.

Both these systems[15,16] are believed to function almost wholly on the basis of impaction (i.e., the drops of water are essentially fired like bullets at the dust particles). The collection efficiencies have been

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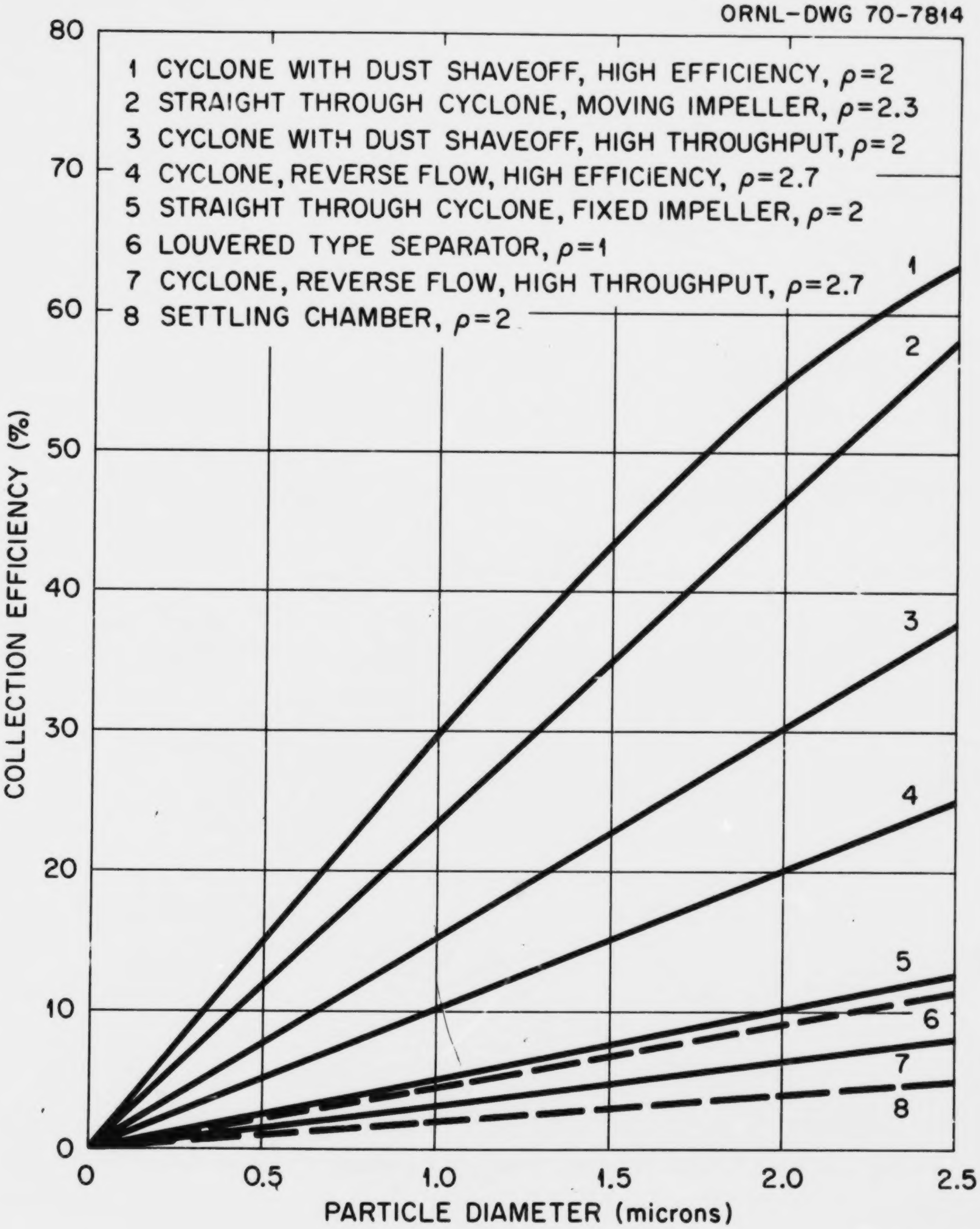

Figure 7. Particle Collection Efficiency of Dry Inertial Devices.

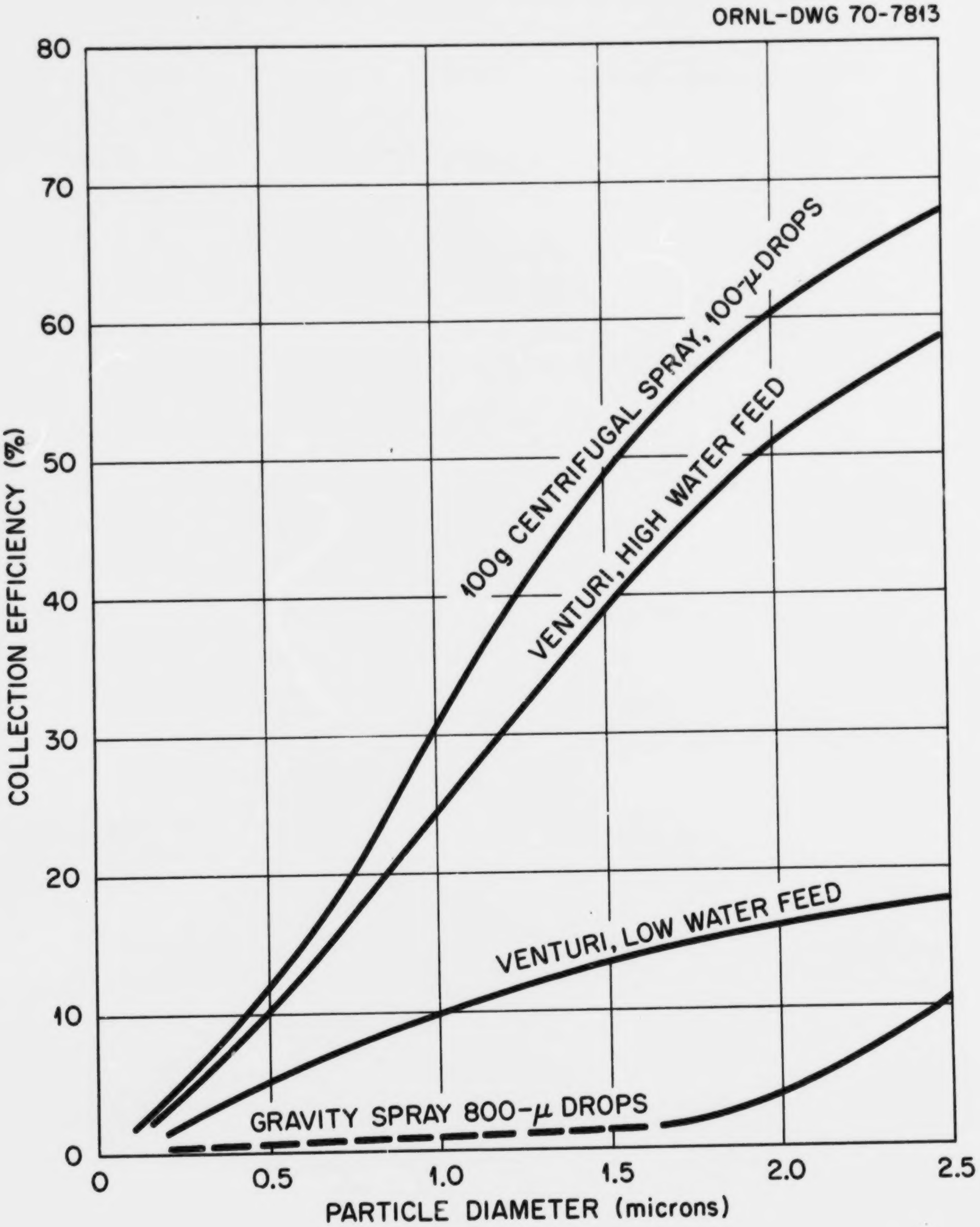

Figure 8. Particle Collection Efficiency of Wet Scrubbers.

correlated with the power used[17] (i.e., the harder the bullets are fired the more difficult it is for the dust particle to get out of the way). Although the possibility of particle deposition due to thermophoresis and/or diffusiophoresis in wet scrubbers has been mentioned,[15] there appears to have been no organized effort to optimize scrubber designs to make use of these driving forces.

Figure 9 shows the collection efficiency of electrostatic precipitators as a function of particle size. These collection efficiencies were estimated from apparent drift velocities[18] which were measured as a function of particle size. The estimates (as indicated) are for a system in which the collecting area per unit of volume flow was such that the removal efficiency of large (> 10 micron) particles would be 99%. The second curve is for the same precipitator which has become loaded with a 10 mm thick layer of dust. Such a dust cake has been indicated[15] to reduce the drift velocity to about 55% of that with clean electrodes. So electrostatic precipitators also fail to collect the 0.2-2 micron particles efficiently.

In summary, the only available systems, that this effort found, for efficiently removing 0.2-2 micron diameter particles from industrial effluents are filters. It is likely that the only type of filter economically adaptable to industrial effluents is the bag filter.

It is suggested that work to develop other collection systems and to understand the deposition mechanisms on which such systems will depend is of high priority.

D. The Basic Mechanisms of Particle Deposition and Particle Growth Due to Condensing Steam

1. Deposition Due to Diffusiophoresis and Thermophoresis

Diffusiophoresis results from the force on particles due to a flux of diffusing molecules. Near a surface onto which water is condensing, there is a flux of diffusing water molecules which tends to sweep particles toward the condensing surface. There is a companion force called thermophoresis which results in particles moving in a temperature gradient toward a cold surface. This results from hotter molecules hitting the particle harder on one side than the cooler molecules hit the particle on the other side. Thermophoresis will add to diffusiophoresis. Goldsmith[19] described

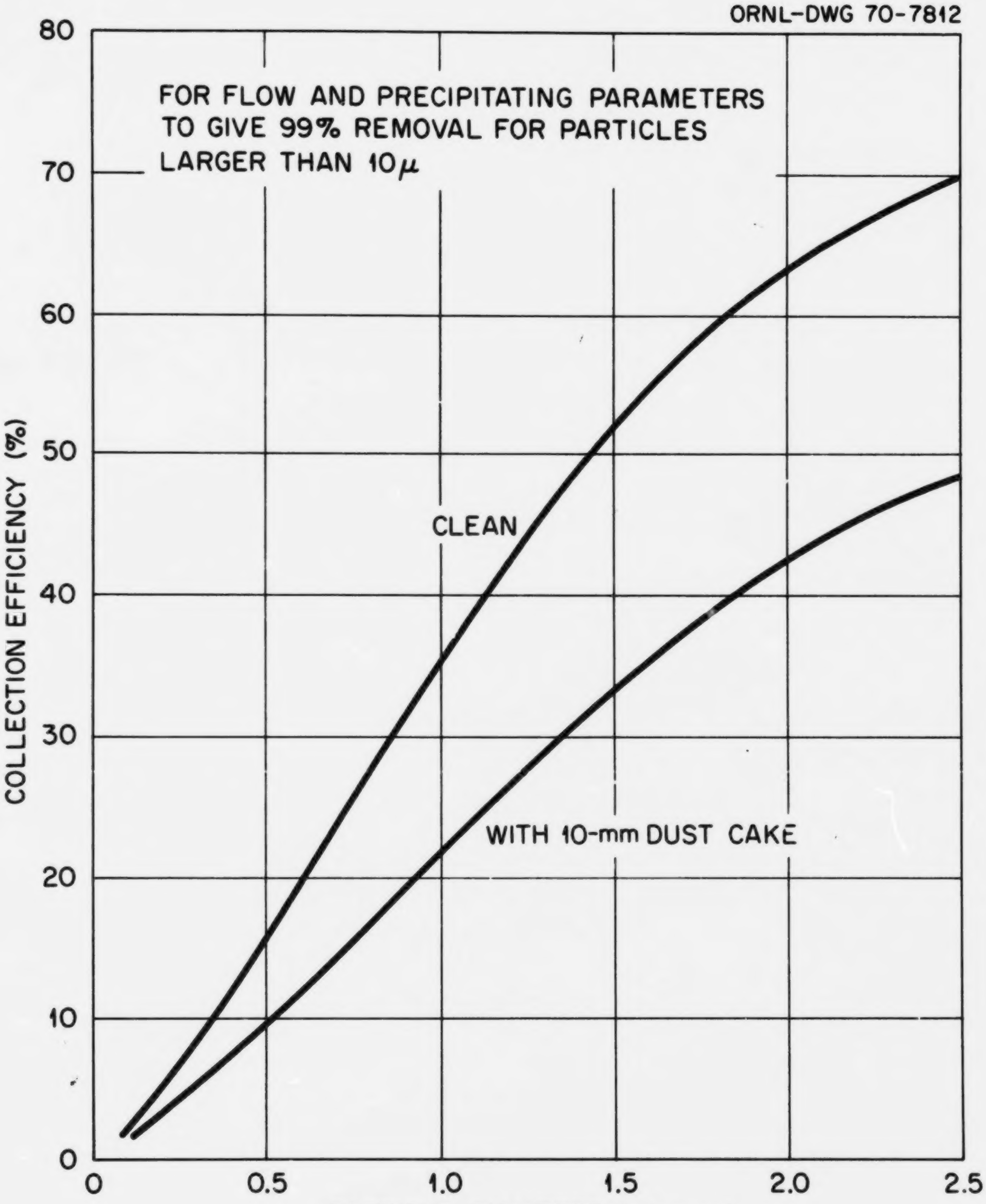

Figure 9. Particle Collection Efficiency of Electrostatic Precipitators.

the process of diffusiophoresis and reported results from some elegant experiments. He showed both theoretically and experimentally that for ordinary (temperature and pressure) conditions, the velocity of a particle, V_G(cm/sec), in a concentration gradient of water molecules, dC/dr' (g water per cm^3 per cm) is about:

$$V_G = - 257\ dC/dr' \tag{2}$$

The rate of condensation of water, dm/dt (g/sec) is also related to the concentration gradient, to the area for condensation, A(cm^2) and the diffusion coefficient for water in air, D ($\sim$ 0.29 cm^2/sec), according to Fick's first law:

$$\frac{1}{A}\frac{dm}{dt} = - D\frac{dC}{dr'} . \tag{3}$$

Combination of Eqs. (2) and (3) and inclusion of the value for D gives

$$V_G = \frac{886}{A}\frac{dm}{dt} . \tag{4}$$

Equation (4) relates the velocity of the particle, V_G, toward a surface of area A, on which water is condensing at a rate dm/dt.

Similarly, the deposition velocity (i.e., the velocity of a particle in a temperature gradient) due to thermophoresis has been measured by Goldsmith[19] and found (in agreement with theory) to be about

$$V_T = - \frac{0.078}{T}\frac{dT}{dr'} \tag{5}$$

where T is the absolute temperature (°K) and dT/dr' is the temperature gradient (°C/cm). The temperature gradient is also related to heat transfer across the zone of the temperature gradient by conduction according to:

$$\frac{dq_c}{dt} = - kA\frac{dT}{dr'} \tag{6}$$

where dq_c/dt is the heat transfer rate in watts, A is the area and k is the thermal conductivity (which is about 2.8×10^{-4} watt sec/cm sec °C for air).

Combining (5) and (6), substituting the numerical value for K (the thermal conductivity) and taking a value of 373°K for the absolute temperature yields:

$$V_T = \frac{0.746}{A}\ \frac{dq_c}{dt} . \tag{7}$$

One can go a step further and express the deposition velocity due to thermophoresis (as in Eq. 7) in terms of the rate of steam condensation. This will allow a direct comparison of the efficiency of the two processes; diffusiophoresis and thermophoresis. For each gram of water condensed, 2.26 x 10^3 watt-sec of heat will be transferred, hence:

$$\frac{dq_L}{dt} = 2.26 \times 10^3 \frac{dm}{dt} \qquad (8)$$

where q_L refers to latent heat of condensation and dm/dt is steam condensation rate (g/sec) as before. On substituting into Eq. (7):

$$V_T = \frac{1686}{A} \frac{dm}{dt}\ . \qquad (9)$$

Comparison of (9) with (4) shows that thermophoresis is about 1.9 times as efficient (i.e., 1686/886) as diffusiophoresis in the use of the steam condensation, to sweep particles to a cold surface.

Recall that diffusiophoresis (Eq. 4) will apply if the water condenses directly onto cold walls and thermophoresis (Eq. 9) will apply if the water condenses on particles. Where the water condenses cannot be readily predicted; it will probably depend on whether the particles are hydrophobic, hydrophillic or hygroscopic, on the degree of water supersaturation and perhaps on particle size.

The magnitude of these deposition velocities can be readily compared to gravitational settling velocities as follows. A one-micron diameter, unit density particle falls at 0.0035 cm/sec.[20] To achieve the same velocity with diffusiophoresis (according to Eq. 4) would require a steam condensation rate of 4 x 10^{-6} g H_2O/sec-cm^2. With thermophoresis (according to Eq. 9) a condensation rate of about 2 x 10^{-6} g H_2O/sec-cm^2 would be necessary.

We wish to suggest the economy of thermophoresis as a particle removal mechanism in comparison to mechanisms such as electrostatic precipitation and centrifugation, which are now widely employed. We will not consider diffusiophoresis separately since we know it and thermophoresis are about equally efficient. Since large scale thermophoretic systems have not been designed, the comparison cannot be on the basis of "operating experience". Instead we will compare the energy consumption required for the three sweeping mechanisms: thermophoresis, electrostatic precipitation and centrifugation.

Fortunately, data are available to allow the comparison to be made on the basis of observations rather than theoretical predictions. Specifically, the comparisons will be made on the basis of the ratio of observed deposition velocities of particles to the energy flux required. In general, this parameter will be particle size dependent; so the dependence of deposition velocity per unit of energy flux will be estimated as a function of particle size for the three deposition mechanisms.

Fuchs[21] reported deposition velocities, V_T (cm/sec) of particles, in a thermal gradient of 49.9 °C/cm, as a function of particle diameter. The gaseous medium was nitrogen. Some points from Fuchs[21] curve (of deposition velocity vs particle diameter) are given in the first two columns of the table below.

We estimated the energy flux as follows. To maintain a thermal gradient in air, a heat flux of q ergs per A cm^2 per t seconds is required according to the equation for thermal conductivity:

$$F_T = \frac{q}{At} = K \frac{dT}{dX} \qquad (10)$$

where K is the thermal conductivity in units of ergs/sec cm^2 (deg/cm). For air K has a value of 2.7×10^3. So the energy flux, F_T is equal to K (dT/dX) and:

$$F_T = K(dT/dX) = 2.7 \times 10^3 (49.9) = 1.36 \times 10^5 \text{ ergs/cm}^2 \text{ sec.} \qquad (11)$$

The desired parameter, V_T/F_T, the deposition velocity over the energy flux is readily evaluated and appears below. We can now plot V_T/F_T vs particle diameter to get the curve labeled "thermophoresis" on Fig. 10.

Deposition Velocities in a Thermal Gradient

d Particle Diameter (microns)	V_T Deposition Velocity (cm/sec)	V_T/F_T Deposition Velocity / Energy Flux (cm/sec)/(ergs/cm^2sec)
		$\times 10^{-8}$
0.1	0.012	8.8
0.2	0.011	8.1
0.4	0.009	6.6
0.8	0.0065	4.8
1.2	0.0045	3.3
1.6	0.004	3.0
2.	0.004	3.0
3.	0.004	3.0

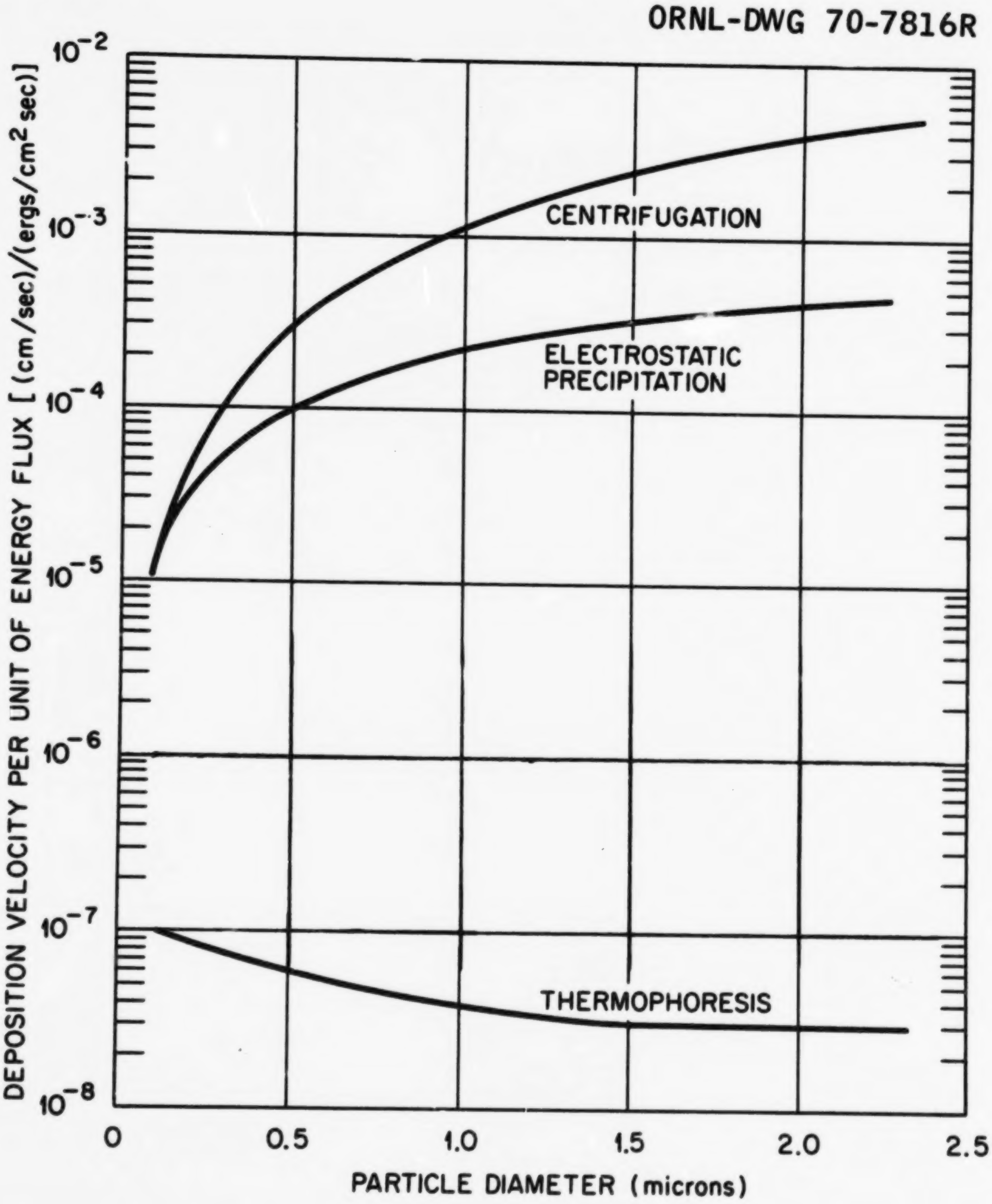

Figure 10. Comparison of Economy of Energy in Particle Sweeping Mechanisms.

Heinrich[22] reported apparent drift velocities under electrostatic precipitator conditions: an applied potential of 45 KV which corresponded to a current of about 14 $ma/10^3ft^2$. He found that for small particles the apparent drift velocity varied with particle size approximately according to:

$$W = 1.5\ d \qquad (12)$$

where the drift velocity W is in cm/sec and the particle diameter, d, is in microns.

Electrical energy is the product of potential, current and time. The energy flux (energy per unit area and per unit time) in such a system is therefore:

$$F_E = Ei_e \times 10^7 \qquad (13)$$

where E is in volts, i_e is the current density in amps/cm^2. The factor 10^7 converts from joules to ergs; hence F_E is ergs/cm^2sec. In Heinrich's experiment, E was 4.5×10^4 and i_e was 1.5×10^{-8} amps/cm^2, hence:

$$F_E = (4.5 \times 10^4)(1.5 \times 10^{-8})(10^7) = 6.75 \times 10^3 \text{ ergs/cm}^2\text{sec} \qquad (14)$$

The quotients, W/F_E were calculated and plotted vs particle size on Fig. 1. The curve through those points is labeled "electrostatic precipitator".

In a gravitational field, the deposition velocity, V_f (cm/sec) is given by Stokes' Law:

$$V_f = \frac{\rho_p h d^2_{cm}}{18\eta}\ C(d) \qquad (15)$$

where ρ_p is the particle density (g/cm^3), g is the acceleration in the gravitational field (cm/sec^2), d_{cm} the particle diameter (cm), η is the viscosity of the medium (g/cm sec) and C(d) is the slip correction which is a function of particle diameter.

The energy flux in such a field is given by an equation analogous to Eq. (10) which is for heat flux in a thermal gradient. The pressure gradient (dP/dx) corresponds to the thermal gradient and the kinematic viscosity ν corresponds to the thermal conductivity. Hence:

$$F_g = \nu\frac{dP}{dX} \qquad (16)$$

where F_g is ergs/cm^{2}sec, ν is in units (cm^2/sec) and (dP/dX) is force per cm^3 (g/sec^{2}cm^2). We need to recall that kinematic viscosity ν is related to η, the viscosity (g/cm sec) of the medium and ρ the density of the medium:

$$\nu = \eta/\rho. \tag{17}$$

Also recall that the pressure gradient is given by:

$$dP/dX = \rho g. \tag{18}$$

Hence, on combining equations (16), (17), and (18),

$$F_g = \eta g. \tag{19}$$

The deposition velocity over the energy flux is therefore:

$$\frac{V_f}{F_g} = \frac{\rho_p d^2_{cm} C(d)}{18\eta^2} \tag{20}$$

For air, $\eta = 1.82 \times 10^{-4}$ and for a particle density, ρ_p, of unity,

$$\frac{V_f}{F_g} = 1.68 \times 10^{-2} d^2_{\mu}\ C(d). \tag{21}$$

Note that d is now in microns.

Thus far we have dealt with theoretical estimates. It is found that in actual cyclone separators, the energy flux (indicated by the pressure drop) is larger than that corresponding to the kinetic energy of the aerosol by a factor ζ, called the loss factor.[23] ζ has a value of about 17 for ordinary cyclones; hence:

$$\frac{V_f}{F_g} = 10^{-3} d^2_{\mu}\ C(d). \tag{22}$$

Values of V_f/F_g were calculated according to Eq. (22) and were plotted on Fig. 10. The curve through those points is labeled "centrifugal separator".

In summary there are two points to be made with reference to Fig. 10. First, of course, thermophoresis by itself is considerably less efficient (with respect to energy consumption) in sweeping particles than the other two processes considered. It is clear, therefore, that any use of condensing steam in scrubbers will not be a direct application of thermophoresis; some indirect use, in conjunction with other processes which make use of particle growth may be useful. It is important to note that thermophoresis uses energy in the form of heat (rather than work). Commonly heat is a less expensive commodity than work; i.e., steam may be cheaper than electricity.

A second point is that thermophoresis is peculiar in that it is a more efficient sweeping process for small (< 1.5μ) particles than for larger ones. Since it is the small particles that constitute particulate urban air pollution, this may be important.

2. Growth Due to Steam Condensation and Turbulent Agglomeration

Growth by steam condensation comes down to a consideration of three possible kinds of behavior and their consequences: First the water may not condense on the particles at all. Second, the water may condense on all the particles so that each particle receives its equal share of growth. Third, the water may condense on some of the particles so that some undergo considerably growth, the rest no growth.

The choice of behavior will likely depend in an important way on whether the particle is hydrophobic, hydrophillic or hygroscopic. We need therefore to define these three words. Hydrophobic and hydrophillic are readily defined in terms of the shapes of the water adsorption isotherms as defined originally by Brunauer.[24] Hydrophillic surfaces will have Brunauer's Type I or II adsorption isotherm for water adsorption. This means that those surfaces encourage the condensation of the first monolayer of water molecules; the first layer is adsorbed at fairly low water vapor partial pressures. Subsequent to the adsorption of the first monolayer the surface acts approximately like a drop of water toward further condensation. Hydrophobic surfaces will have a water adsorption isotherm similar to the Brunauer Type III adsorption isotherm which means that adsorption of the first monolayer is resisted; a water molecule will prefer to adsorb on top of a previously adsorbed water molecule than on the free hydrophobic surface. The effect is that essentially no adsorption occurs until water vapor supersaturation of some level (characteristic of the surface) is reached then adsorption of the first monolayer occurs. The surface is now covered with water and will act approximately like a water drop toward further condensation; so condensation of several more layers will occur until the water vapor pressure is down to equilibrium.

Hygroscopic particles are also hydrophillic in that they encourage the first monolayer of water molecules; in this case, however, the reaction with water is absorption rather than adsorption. Hygroscopic particles will continue to react with water at low partial pressure as long as there is particle substance left to react or commonly until so much water has been absorbed that the particle has become a dilute aqueous solution. Water soluble substances are commonly hygroscopic.

Now to consider the three kinds of growth behavior in condensing steam. The first case is the one in which the water does not condense on particles at all; it condenses on cold walls. In this case the deposition mechanism will be diffusiophoresis (as described above). This kind of behavior would tend to occur where the driving force for condensation is small. This would be with hydrophobic particles; it would tend to occur where the water vapor supersaturation was low (i.e., where the driving force for condensation was small). This would tend to occur if water saturated aerosol was slowly cooled or underwent a slow adiabatic expansion. There might also be a particle size effect; water would be less apt to condense on small nuclei than on large ones. This latter effect is a consequence of the fact that the equilibrium vapor pressure over a surface depends on the curvature of the surface; the vapor pressure is higher if the curvature is higher. This means, for instance, that a tiny drop of water (with a highly curved surface) is in equilibrium with a higher partial pressure of water than is a plane surface. This was predicted by Gibbs and demonstrated by LaMer;[25] the relationship which gives the vapor pressure, P, in equilibrimm with a spherical drop of radius, r, of a liquid with surface tension, γ, and density, ρ, at temperature T is:

$$P/P_\infty = \exp\,(2\gamma M/RT\rho r) \tag{23}$$

P_∞ is the normal vapor pressure over a plane surface. For water P/P_∞ is very nearly unity for r greater than about 0.1 microns. It is not readily possible to predict anything quantitative from Eq. (23) about any possible particle size effect on the likelihood of water condensing on a particle of oil or metal oxide or other material, but there would tend qualitatively to be this effect. Water would be more apt to condense on larger particles (of less surface curvature) than on smaller particles.

The second possible behavior was equal growth of all particles. This would tend to occur where the driving force for condensation was large so that every water molecule would condense on the first surface it hit. This would tend to be the case with hygroscopic particles (less so with hydrophillic particles and still less with hydrophobic particles) and at high water vapor supersaturation.

The amount of growth in this case is easy to calculate. The volume of each particle (assumed spherical) before condensation is $(4/3)\pi r_o^3$ (where r_o is the original particle radius) and the volume of water condensed per particle would be $W/\rho N_o$ where W is the mass (g) of water condensed per unit volume (cm^3) of aerosol, ρ is the density of water (g/cm^3) and N_o is the number concentration of particles (no/cm^3). So the volume of each particle after condensation is:

$$(4/3)\pi r^3 = 4/3\pi r_o^3 + W/\rho N_o \tag{24}$$

where r is the droplet radius after condensation. Since we are probably concerned with particles that are originally one micron or less in radius and grown particles that are 3 microns or more in radius, $4/3\pi r_o^3$ is considerably less than $W/\rho N_o$ (i.e., the final particle is mostly water), therefore:

$$(4/3)\pi r^3 = W/\rho N_o \tag{25}$$

and

$$r = (3W/4\pi\rho N_o)^{1/3} \tag{26}$$

Equation (26) can be used to predict settling velocities of the grown particles according to Stoke's law, hence the gravitational settling velocity V_f (cm/sec) is related to the particle density $\rho(g/cm^3)$, the gravitational constant g (cm/sec^2) and the viscosity of the medium η(poise):

$$V_f = \frac{2\rho g r^2}{9\eta} \tag{27}$$

and with Eq. (26)

$$V_f = \frac{2\rho g(3\pi W/4\rho N_o)^{2/3}}{9\eta} \tag{28}$$

It is interesting to consider how much power would be required to make the steam for particle growth. If we rearrange equation (25):

$$W = (4\pi/3)(\rho N_o)r^3. \tag{28a}$$

and putting in a value of unity for ρ and change the units of r from cm to microns:

$$W = 4.19\ N_o r^3 \times 10^{-12} \tag{28b}$$

If we now change the units of W in g water/cm^3 aerosol to W' in hp/1000 ft^3/min according to:

$$W(2.26 \times 10^3 \text{ joules/g } H_2O \text{ vaporized})(2.24 \times 10^{-5} \text{ hp min/joule})$$

$$(2.84 \times 10^7 \text{ cm}^3/1000 \text{ ft}^3) = W' \tag{28c}$$

and

$$W' = 1.44 \times 10^6 W. \tag{28d}$$

and substitute into (28b), then:

$$W' = 6.03 \times 10^{-6}\ N_o r^3 \tag{28e}$$

Values of W' were calculated for assumed values of r (microns) and N_o (particles/cm^3) and are plotted on Fig. 10a. As can be seen, for say, N_o of 10^5 which might be a common value, it would require about 1 hp/1000 ft^3/min to grow particles to about 1 micron in radius. This is a reasonable amount of energy compared to that used, for instance, in inertial impaction devices; they commonly[26] consume 1-10 hp/(1000 cu ft/min).

The third case, that of massive growth of some particles and no growth of others, would probably tend to occur with hydrophobic particles at modest water vapor supersaturation because (as noted above) there will be a tendency with hydrophobic particles for massive growth to occur suddenly like an avalanche. After the avalanche type growth of some particles the water vapor concentration would be low so that the other particles might never get a second chance for growth. Another kind of cause of this third growth behavior is the particle size effect noted above. Big particles grow at a somewhat lower water vapor partial pressure than little ones. This would suggest that under slow growth conditions (perhaps hydrophillic particles at low water vapor supersaturation) some particles would simply become larger as a matter of chance and being larger would grow faster. Growth would again occur only to favored particles.

The amount of growth and the fraction of the particles that undergo growth cannot be estimated because of the several uncertainties. It is probably more important to note that in this case the efficiency of a scrubber might simply be the fraction of particles which grow and therefore improved efficiency would require increasing the water vapor supersaturation.

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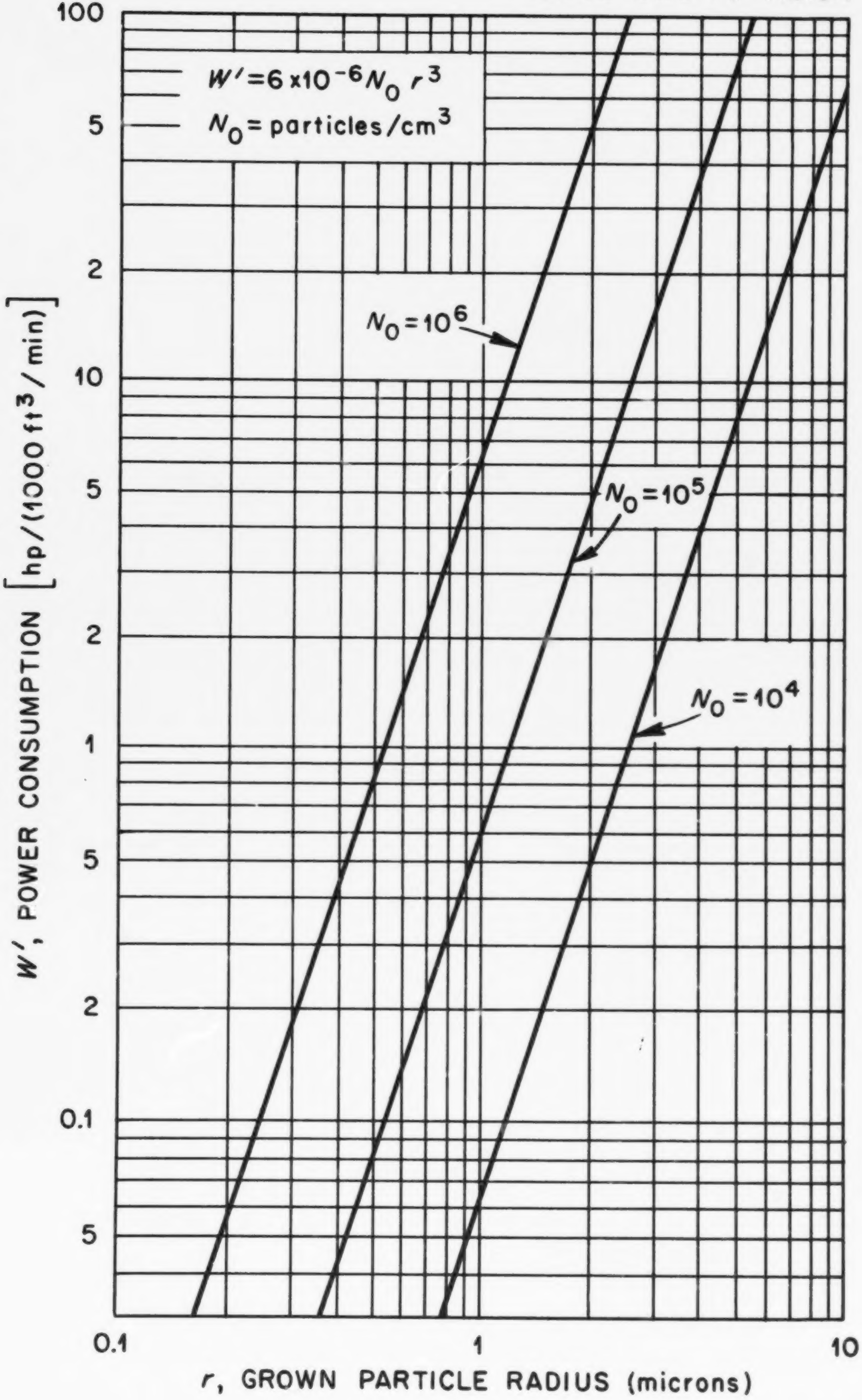

Figure 10a. Power Consumed in Growing Particles by Steam Condensation.

Growth due to turbulent agglomeration has been considered theoretically;[27] it has been estimated that the change in number concentration with time, dn/dt (particles/cm^3 sec) would be proportional to the square of the number concentration, n(particles/cm^3),

$$dn/dt = -Kn^2 \tag{29}$$

with K being

$$K \sim K' \left[(E/\eta)^{1/2} r^3\right] \tag{30}$$

and

$$K' \sim 4 \times 10^{-12} \text{ to } 25 \times 10^{-12} \tag{31}$$

where E is the energy dissipated in turbulence (ergs/cm^3 sec), η is the viscosity of the medium in poise and r is the particle radius in microns. If we take K' to be 10×10^{-12} (a middle value in the range), and η to be 1.83×10^{-4} poise for air, then:

$$K = 7.39 \times 10^{-9} (E)^{1/2} r^3 \tag{32}$$

It is common to express energy used in air cleaning in units of hp/1000 ft^3, hence E' in hp/1000 ft^3 is:

$$E' = (E \text{ ergs/sec cm}^3)(10^{-7} \text{ joules/erg})(0.00134 \text{ hp sec/joule})$$
$$(2.83 \times 10^7 \text{ cm}^3/1000 \text{ ft}^3) = 3.79 \times 10^{-3} E \tag{33}$$

and

$$K = 1.20 \times 10^{-7} (E')^{1/2} r^3 \tag{34}$$

Going back now and substituting into Eq. (29):

$$dn/dt = -1.20 \times 10^{-7} (E')^{1/2} r^3 n^2 \tag{35}$$

Or if we put t in minutes as is common in air cleaning technology:

$$dn/dt = -7.2 \times 10^{-6} (E')^{1/2} r^3 n^2 \tag{36}$$

To proceed further in a very quantitative way to estimate decreases in concentration due to turbulent agglomeration (hence in increases in particle size) would require more mathematical effort than we wish to expend here. We can, however, get a rough idea of the energy consumption to grow particles via turbulence as follows. If we presume that the aerosol is monodisperse (i.e., all particles are the same size) and that they all grow at the same rate (i.e., they stay the same size) then the number concentration will vary inversely as the particle volume, hence:

$$n/n_o = [(4\pi/3) r_o^3]/[(4\pi/3) r^3] \tag{37}$$

or

$$r^3 = r_o^3 \, n_o/n \tag{38}$$

If we substitute equation (38) into (36):

$$dn/dt = -\ 7.2 \times 10^{-6}\ (E')^{1/2}\ r_o^3 n_o\ n \tag{39}$$

or

$$dn/n = -\ 7.2 \times 10^{-6} (E')^{1/2}\ r_o^3 n_o dt \tag{40}$$

On integrating from $n = n_o$ at $t = 0$ to $n = n$ at t:

$$\ln n/n_o = -\ 7.2 \times 10^{-6}\ (E'/t)^{1/2} r_o^3 n_o t^{1/2} \tag{41}$$

(where the group $(E'/t)^{1/2}$ has been put together in order to get the unit $hp/10^3 ft^3/min$)which Semrau[26] used in comparing energy consumption among inertial devices. To be systematic, we will call E'/t, W' as previously. He found that W' was commonly about 1-10 hp/(1000 ft^3/min) for inertial separators.) If we now replace the ratio n/n_o in Eq. (41) with the ratio $(r/r_o)^3$ from Eq. (38);

$$\ln r/r_o = 2.16 \times 10^{-5}\ W'^{1/2} r_o^3 t^{1/2} n_o \tag{42}$$

Some values of W' have been calculated from Eq. (42) for an assumed value for t of 1 min, for n_o of 10^5 and for a variety of values of r_o (radius in microns before turbulent growth) and of r (the final radius). These values are shown on Fig. 10b.

These values (on Fig. 10b) suggest that we need to grow the particles just a little bit by condensation, i.e., up to a radius of about 1 to 1.5 microns, then turbulent agglomeration might cheaply grow them up to sizes which would settle or be readily impacted in a cyclone or other inertial device. Of course, this estimation is very approximate.

E. Applications of Steam Condensation in Scrubbers

Scrubbing by steam condensation has not been systematically studied (hence the present study is necessary). However, there are several pertinent efforts that should be described.

First there is the correlation of Semrau[17] which shows us the amount of power consumed in present-day inertial devices; this provides a target. We need to accomplish fine particle removal with a similar or smaller energy consumption. Second, another correlation by Semrau et al.[27] indicates the order of magnitude difference in collection efficiencies of certain devices with steam condensation working for particle deposition vs no steam condensation or possibly water vaporization working against

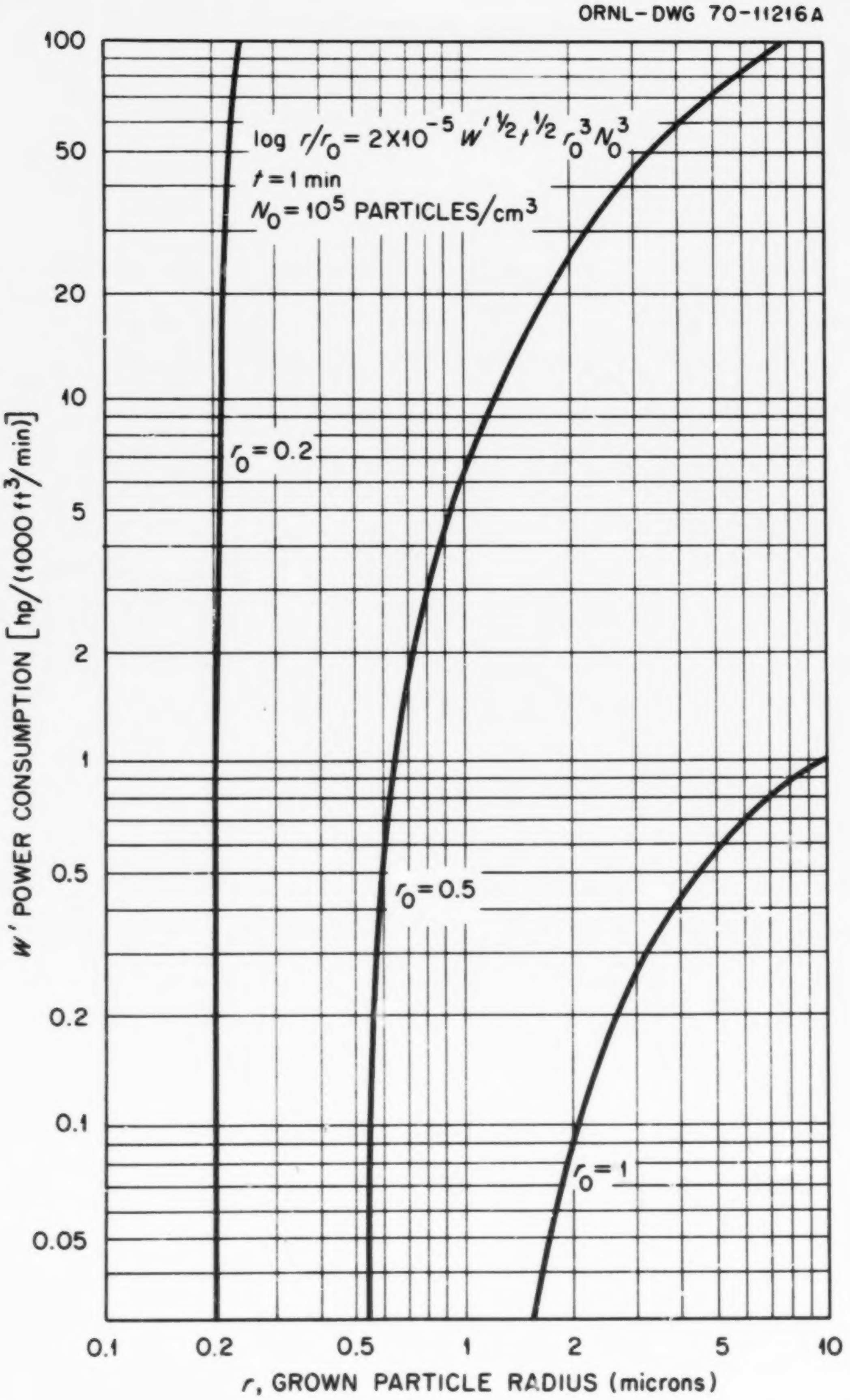

Figure 10b. Power Consumed in Growing Particles by Turbulent Agglomeration.

particle deposition. Third a few experiments by Schauer[28,29] have suggested that excellent removal efficiencies are possible in a system where particles were grown in condensing steam then impacted out in a Pease-Anthony spray tower. Fourth some experiments by Goldsmith[30] are reviewed which are somewhat similar to the experiments in this study.

The correlations of Semrau[17] are shown on Fig. 11. The removal efficiencies of an assortment of wet scrubbers are shown as a function of power consumption in the scrubber. The removal efficiencies are given as percent removed on the right ordinate and as transfer units on the left ordinate. The number of transfer units, N_t, was defined by Semrau in terms of the fraction of particles removed η according to:

$$N_t = \ln\,[1/(1-\eta)]. \qquad (43)$$

This correlation shows a considerable range of power consumption for a given removal efficiency. The range is probably due largely to the difference in aerosol concentrations and particle sizes but the data which were available to Semrau were insufficient to make any inferences about effects of particle parameters. The correlation showed that the removal efficiency of each aerosol and with each scrubber (expressed as number of transfer units) increased with contacting power according to equations of the form:

$$N_t = \alpha P_T^{\gamma} \qquad (44)$$

where P_T is contacting power. This suggests that high removal efficiencies uniformly require high contacting power (and the associated high cost). The correlation also provides us with the order of magnitude of contacting power values which is apparently economically acceptable; it appears that 1-10 $\mathrm{hp}/10^3\mathrm{ft}^3$ is an acceptable power consumption.

Semrau[27] also accumulated some results which indicate that significant reductions in power consumption have been enjoyed in wet scrubbers due to steam condensation effects. Figure 12 shows the pertinent results plotted again as number of transfer units vs contacting power. The "Venturi and cyclonic spray scrubbers" used cold water to scrub water vapor saturated aerosol; this (it was suggested) allowed relatively high removal efficiencies with given power costs. The "pipe line scrubber" used a hot solution to scrub saturated aerosol; less condensation would have resulted and the removal efficiency for a given power cost was less. Finally, the dashed

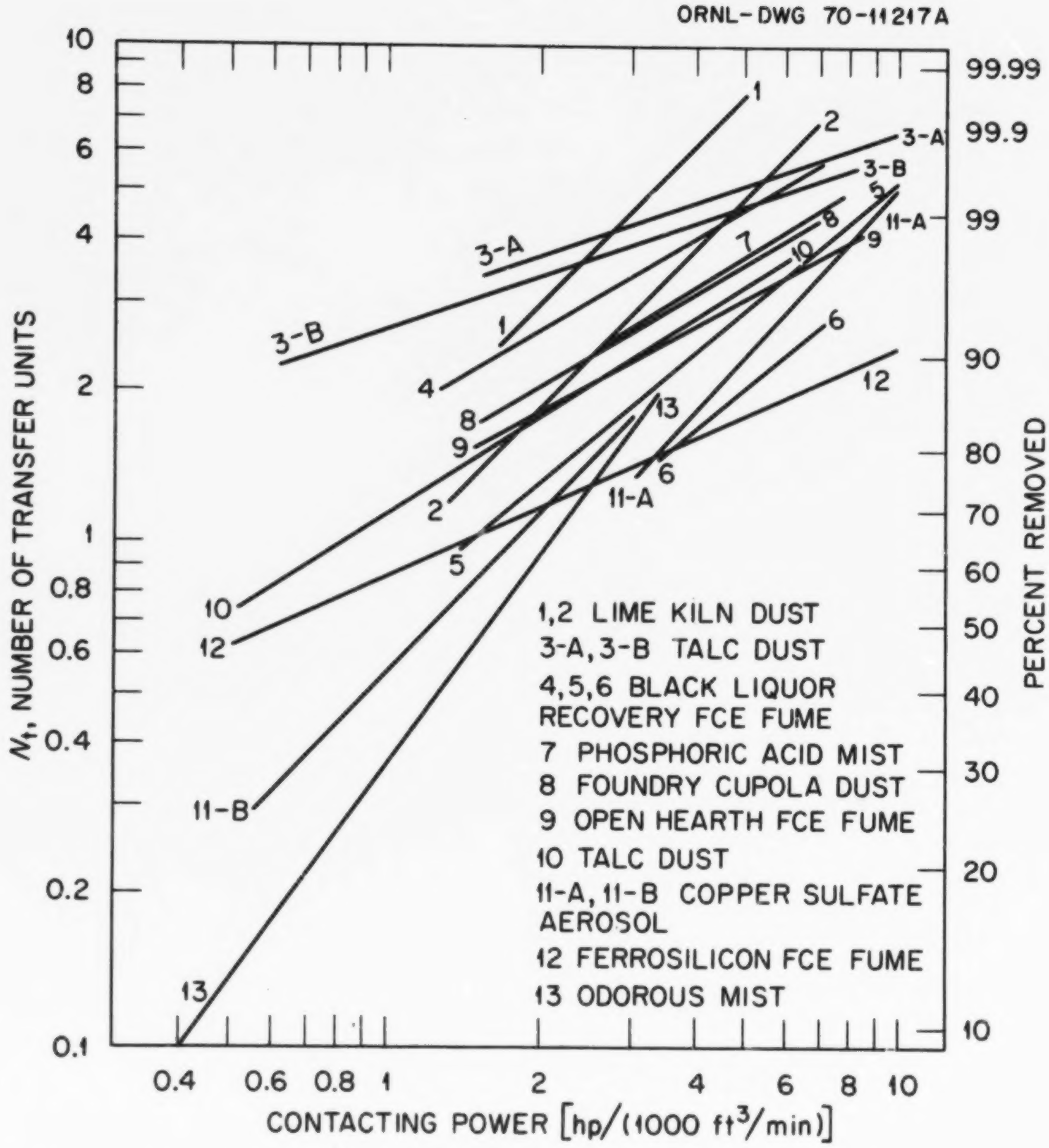

Figure 11. Performance Curves for Scrubbing of Some Aerosols.

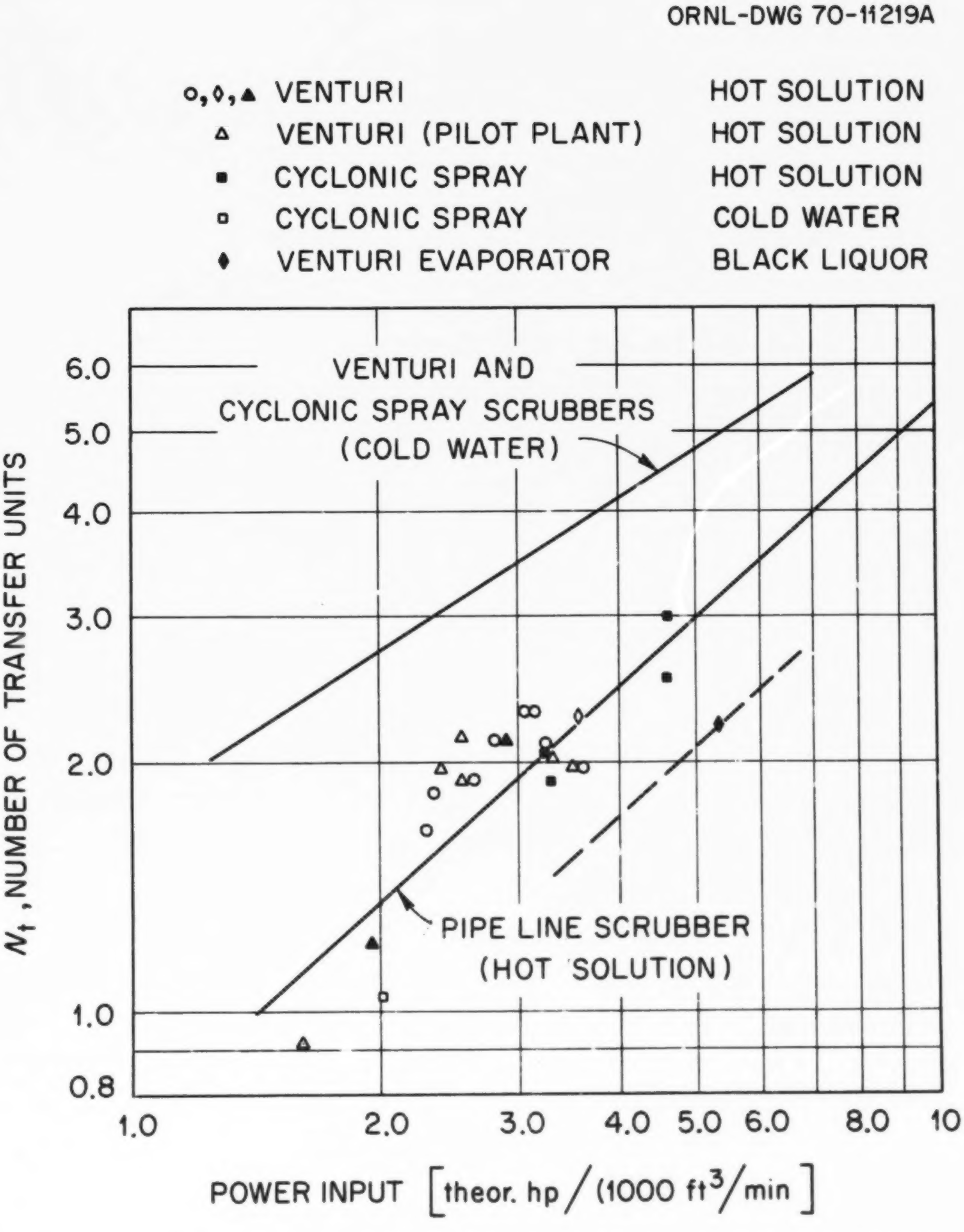

Figure 12. Performance of Pilot Plant Scrubbers on Sulfate Recovery Furnace Fume. K. T. Semrau, C. W. Marynowski, K. E. Lunde, C. E. Lapple, Ind. Eng. Chem. 50, 1615-1621 (1959).

line is for a case in which a Venturi was used with dry aerosol. In this case water was probably vaporizing from the drops of scrubbing liquor and the steam condensation mechanisms were retarding particle deposition onto the drops of scrubbing liquor. In any case the removal efficiencies were still smaller for given power inputs. In the extreme, the power costs (say to achieve 2 transfer units) differed by a factor of about 5; it is clear that steam condensation can save power, hence save money.

Some interesting tests were done by Schauer[28,29] in a pilot plant scrubber indicated schematically on Fig. 13. Steam at a gage pressure of 44 $lb/in.^2$ was allowed to expand through the nozzle to atmospheric pressure. The nozzles were equipped with inlet ports in the first expansion stages. A test aerosol of 0.3 micron diameter DOP (dioctylphthalate) particles was employed; it was either sucked into the single expansion nozzle through the inlet ports or pumped into the double expansion nozzle at 22 $lb/in.^2$ A second aerosol of smoke from burning trash was used. A ratio of 1 part aerosol to 2.3 parts steam by weight was employed (taking air as having a density of 0.0012 g/cm^3, this corresponds to 0.0028 g H_2O/cm^3 of aerosol or in terms of energy requirement to make the steam, 3.7×10^4 $hp/1000\ ft^3/min$. The expanded aerosol passed directly to a cooled chamber and then through a Pease-Anthony spray tower. With the DOP aerosol the results were excellent; the removal efficiency of the system was zero without steam, 98% with the single stage nozzle and 99.9% with the double expansion nozzle. With the smoke from a trash (paper, rubber, cloth and plastic) fire, the removal efficiency (with the double expansion nozzle) was much poorer, namely about 90%. Schauer's few results illustrate that high removal efficiencies are possible, however, his actual system used much too much steam to be economically practical. The results indicate that indeed more systematic study could pay off.

Finally, we need to consider the experiments of Goldsmith and May[30] which were similar in some ways to the experiments described in this report. They mixed an aerosol of oxide particles formed by heating a nichrome wire in air (particle size about 0.05 to 0.5 micron diameter) with steam and led the mixture into the top of a simple condenser. The condenser was a glass tube, 5 cm diameter 50 cm long,water-cooled on the outside. The effluent apparently came out of the side of the condenser near the bottom

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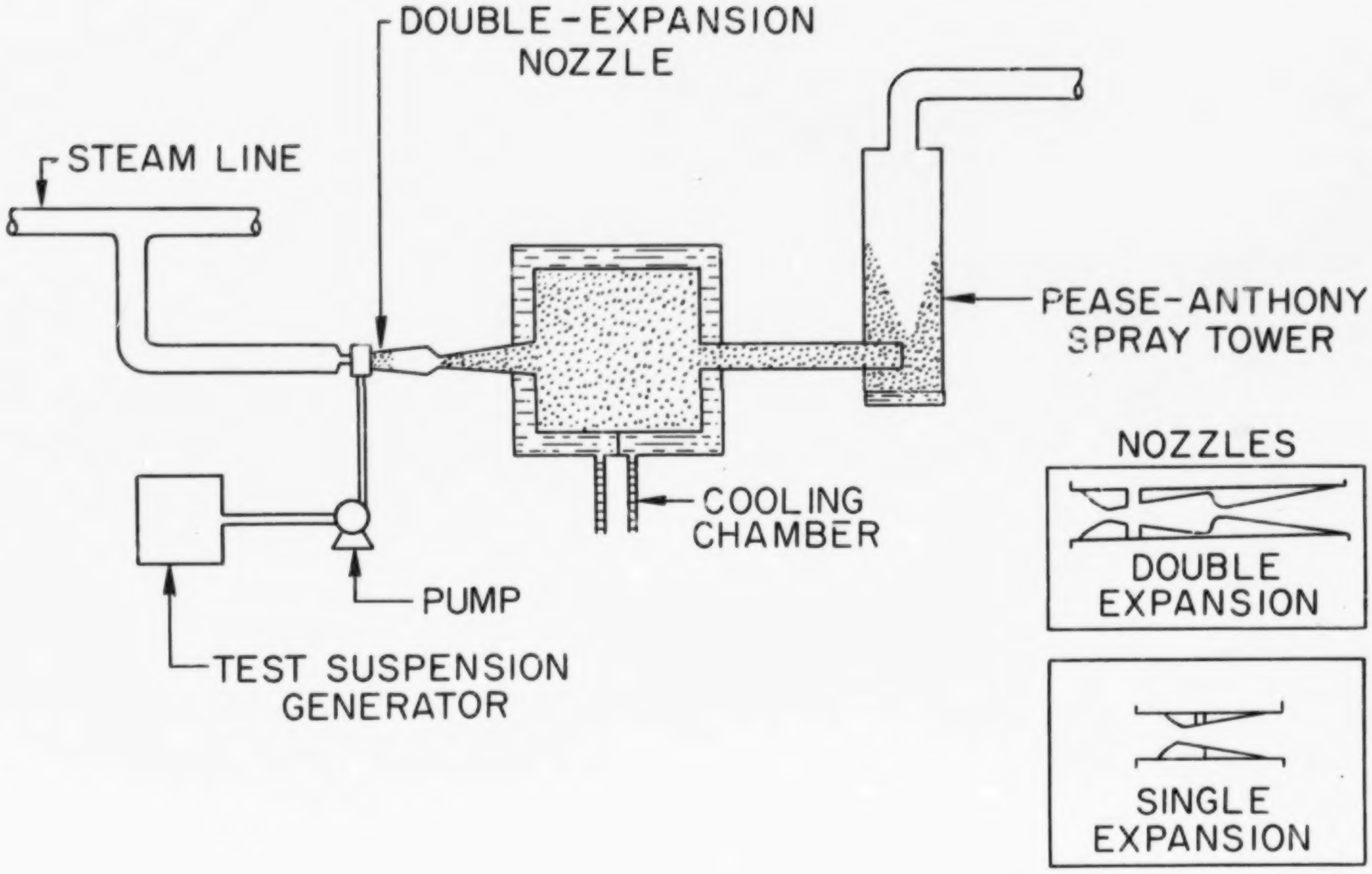

DOUBLE-EXPANSION NOZZLE
STEAM LINE
PEASE-ANTHONY SPRAY TOWER
NOZZLES
COOLING CHAMBER
PUMP
TEST SUSPENSION GENERATOR
DOUBLE EXPANSION
SINGLE EXPANSION

Figure 13. Schauer's Apparatus for Producing Condensation by Adiabatic Expansion. P. J. Schauer, MLM-490, Sept. 1, 1950.

(i.e., there was an elbow at the bottom). They measured inlet and outlet concentration, both number and mass concentration. The ratios of outlet to inlet mass and number concentration were of similar values. The steam condensation rate (g H_2O/cm^3 aerosol) and the velocity through the tube were varied. The results are shown on Fig. 14 as the dashed lines; the plot is of the ratio of the outlet to the inlet concentration vs steam condensation rate; each dashed line is for a different aerosol velocity.

One point from these experiments is simply to consider the removal efficiency achieved in the best case, i.e., about 98% removal (i.e., outlet to inlet concentration ratio of 0.02) with about 2×10^{-4} g/cm^3 condensation rate. This corresponds to about 2.9×10^2 hp/1000 ft^3/min (of power to generate the steam used). The power for steam generation is still large compared to the 1-10 hp/1000 cu ft consumed in inertial scrubbers.

The other points of interest from these experiments are derived from the simple geometry employed which allows one to simply predict the removal efficiency expected as a consequence of deposition on the walls by diffusiophoresis and by thermophoresis. In this experiment turbulence can be presumed to maintain the concentration every where the same, except in the stagnant boundary layer near the cool wall. There is a flux of condensing water molecules and a temperature gradient across this boundary layer. Any particle which gets caught in the boundary layer falls prey to the forces of thermophoresis and diffusiophoresis.

Consider a succession of disc-shaped increments in the condenser. The change in the number of airborne particles from one increment to the next is given by: $- V_H \pi R^2 (dN)$ where V_H is the linear vertical velocity of the particles, R^2 is the cross sectional area of the condenser (i.e., πR is the radius of the condenser) and dN is the change in number concentration of particles from one disc increment to the next. This quantity of particles will be equal to the number which deposited onto the wall within the increment, which is given by: $(V_R N)(2\pi R)(dH)$ where V_R is the radial velocity of particles, N is the number concentration [so that $(V_R N)$ is the flux of particles to the wall], $(2\pi R)$ is the circumference of disc increment and dH is the height of the increment [so that $2\pi R(dH)$ is the area for deposition]. These two quantities are equal:

$$- V_H \pi R^2 (dN) = V_R N 2\pi R (dH). \qquad (45)$$

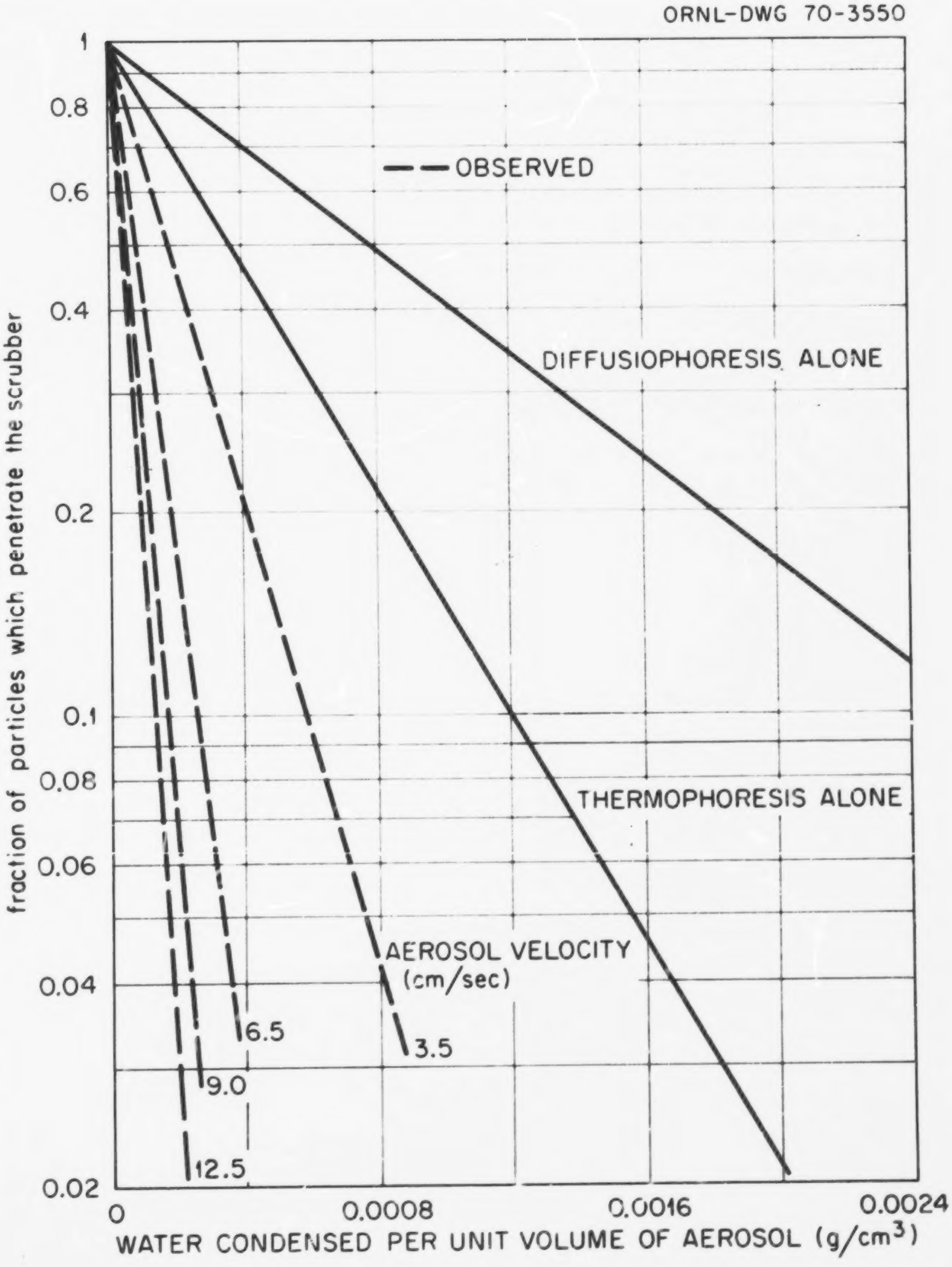


Figure 14. Efficiency of a Condenser Scrubber.

Rearrangement and integration from $N = N_o$ at $H = 0$ to $N = N$ at $H = H$ results in

$$\log N/N_o = \frac{2V_R H}{2.303\ V_H R}\ . \tag{46}$$

Note that the fraction H/V_H is the residence time for particles in the column. (This idea will be made use of later.)

Now it is more convenient to express the vertical velocity up the condenser in terms of volume flow rate, V_A cm^3/sec, which is related to the linear velocity V_H and the cross-sectional area, πR^2 as follows:

$$V_H = V_A/\pi R^2. \tag{47}$$

Therefore on substituting (47) into (46):

$$\log N/N_o = \frac{2\pi R V_V H}{2.303\ V_A}\ . \tag{48}$$

Of course, $2\pi RH$ is the total area of deposition, A, hence:

$$\log N/N_o = V_R A/2.303\ V_A. \tag{49}$$

The term V_R, the velocity of particles through the stagnant film to the cold wall, is simply the deposition velocity due (let us say) to diffusiophoresis only, hence V_R is equal to V_G as defined in Eq. (4). On substituting the value of V_G in Eq. (4) for V_R in Eq. (49):

$$\log N/N_o = -\frac{385}{V_A}\left(\frac{dm}{dt}\right), \tag{50}$$

where (dm/dt) is the rate of condensation of water in the condenser (in g/sec) and V_A is the aerosol velocity up the condenser (in cm^3/sec). The quotient (dm/dt) divided by V_A is simply the mass of water condensed per unit volume of aerosol, let's say, W g/cm^3, hence:

$$\log N/N_o = -\ 385\ W. \tag{51}$$

A curve of calculated values of the fraction (of number or of mass) of particles which penetrate the condenser (i.e., N/N_o) vs the water condensed per unit volume (i.e., W) is given in Fig. 14. It is labeled diffusiophoresis.

If the effective process which sweeps particles through the stagnant film is thermophoresis then (the deposition velocity, V_T according to Eq. 9 is substituted in Eq. 49 and) the derivation proceeds similarly to that above for diffusiophoresis to give:

$$\log N/N_o = -\ 730\ W. \tag{52}$$

Values from Eq. (52) are shown in Fig. 14; the curve is labeled thermophoresis.

Now, as indicated previously the diffusiophoresis line (on Fig. 14) should have predicted the results if the water had condensed mostly on the wall; this line did not fit any data so apparently the steam condensed on the particles. The thermophoresis line should have fit observed behavior if the steam condensed on particles and there was no subsidiary effect on deposition due to particle growth; the data seem to approach the thermophoresis line at the lowest velocities but the fit is not good in any case. There appears to have been a large effect (i.e., increased removal efficiency) consequent to particle growth; furthermore this increased removal efficiency increased with velocity. It is suggested here that a combination of additional growth by turbulence and impaction of the grown droplets in the elbow at the exit of the condenser may explain the behavior. In any case these data are intriguing; a rather commendable removal efficiency of very fine particles was obtained with a very simple device.

III. Objectives of the Experimental Program

The objectives of the experiments presented were exploratory in nature. It is clear from the above considerations that the sweep deposition mechanisms (of diffusiophoresis and thermophoresis) are not cheap in comparison to other available deposition mechanisms (such as inertial impaction and electrostatic precipitation). If condensing steam is useful, it must be so largely on the basis of particle growth (and the consequent ease of further growth by turbulence and deposition by impaction). It is the logical next step therefore to show that many (if not all) aerosol particle substances and sizes and at various concentrations do in fact undergo growth in condensing steam at reasonable (i.e., even at fairly low) water vapor supersaturation. This next logical step was the objective. To cover the probable range of particle substance behavior we chose convenient examples of hydrophobic, hydrophillic and hygroscopic particle substances. The sizes and concentrations were the ranges available without excessively expensive development.

Subsidiary objectives were to discover as much as possible about the details of the growth and deposition mechanisms associated with condensing steam and deduce as much as possible about the potential economy of fine particle removal with steam condensation.

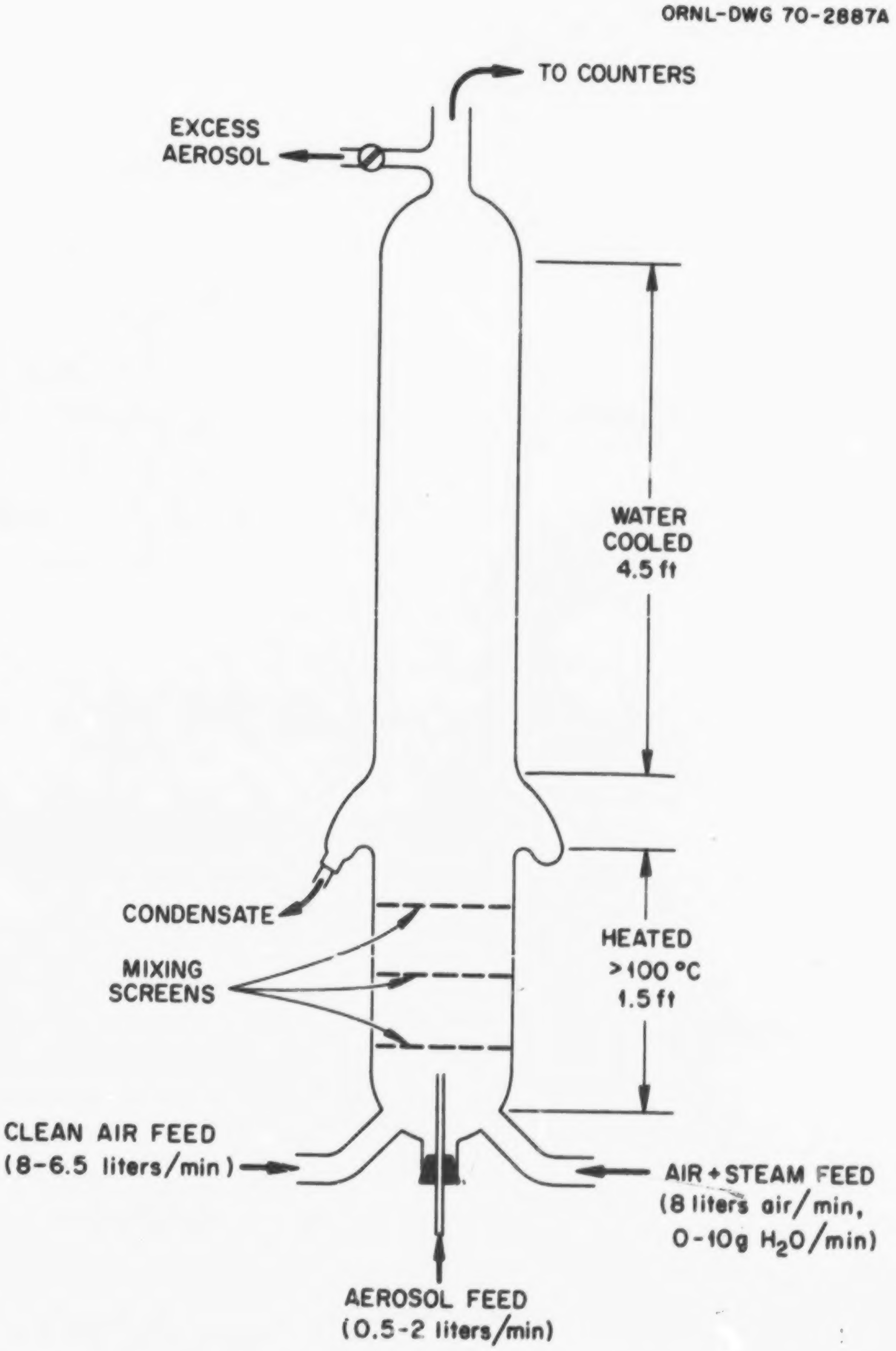
IV. Apparatus, Procedure and Theoretical Basis of Interpretation of Data

A. The Experimental Condenser Scrubber

The experiment is shown schematically in Fig. 15. Basically it is a vertically oriented 4-in. (10 cm) diameter glass pipe. There are three inlet tubes at the bottom to admit aerosol, dilution air and steam-air mixtures separately. The aerosol feed inlet is a quarter-inch tube; the other two are one-inch tubes. The bottom section (18 inches) contains three screens and is heated to slightly more than 100°C;the screens are for mixing the three inlet streams and the heat prevents condensation until after mixing is accomplished. This bottom section also allows the turbulence associated with the inlet stream to be dissipated before condensation begins. There are two outlets at the top; a one-inch pipe to the system of counting instruments and a second outlet through which excess aerosol is discarded. The top section (4.5 feet) of the 4-in.-tube is water-cooled; it is wrapped with a spiral of D-cross section, flexible tubing and tap water runs through the tubing. Between the water-cooled top section and the heated bottom section, there is a (6-in. long) section containing a weir to catch and drain off the condensate which runs down the walls of the water-cooled top section.

We presumed at the outset, on the basis of earlier experiments by Goldsmith[30] that turbulence would be an important parameter. (This is probably because large droplets are coagulated rapidly by turbulence.) In these first experiments, however, we wished not to consider the effects of turbulence but only of other parameters. The heated bottom section with screens was therefore to minimize turbulence. Furthermore, all the experiments were done at the same total air flow rate in order to maintain a constant, low level of turbulence. The air plus steam feed rate always contained 8 liters/min of air (measured at room temperature); in addition, it contained variable amounts of steam (0-10 g of water/min). The aerosol feed rate was 0.5, 1, 1.5, or 2 liters/min and the clean air feed was, respectively, 8, 7.5, 7, or 6.5 liters/min. The sum of the air flows (aerosol feed plus dilution air plus the air in the steam air mixture) was, therefore, always 16.5 liters/min.

The procedure was to first do a control experiment without any steam in which measurements (concentration and size distribution) on the effluent aerosol out the top of the condenser was made. Then steam was added, the system allowed to heat up and come to equilibrium and a second series of measurements was made. This allowed the data to be handled as ratios of values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TO COUNTERS
EXCESS AEROSOL
WATER COOLED 4.5 ft
CONDENSATE
MIXING SCREENS
HEATED >100 °C 1.5 ft
CLEAN AIR FEED (8-6.5 liters/min)
AIR + STEAM FEED (8 liters air/min, 0-10g H2O/min)
AEROSOL FEED (0.5-2 liters/min)

Figure 15. Schematic Diagram of Condenser Scrubber Experiment.

values for wet aerosol to values for dry aerosol and hopefully thereby to improve the accuracy of the results.

B. Theoretical Basis for Particle Removal in the Condenser Experiment

It is convenient here to describe the experimental design criteria of the condenser experiment, i.e., to describe the reasons why it was made as it was, and to derive formulas for anticipated removal efficiency as a function of experimental parameters.

It has been noted that the critical question is where does the steam condense. If it condenses directly onto the cold wall, then particles will move toward the cold wall due to diffusiophoresis as described in Section I-D-1 at a velocity proportional to the steam condensation rate, given by Eq. (4). Particle removal would occur according to the Eq. (51), derived in Section I-E (to explain the results of Goldsmith); it is repeated here:

$$\log N/N_o = -385W \tag{51}$$

where N/N_o is the ratio of outlet to inlet concentration. (It could be either the ratio of number or mass concentration since we expect very little particle size effect.) W is the amount of steam condensed, g of water per cm^3 of aerosol. The Eq. (51) relation is shown on Fig. 16 as the curve labeled "diffusiophoresis".

The other possibility is that water condenses on the particles; in this second case the particles undergo growth and the growth can bring further and usefully important complications. To take the simplest case first, consider condensation onto particles under conditions where the growth does not cause enhanced particle removal. In this case the particle would drift toward the wall due to thermophoresis at a velocity given by Eq. (9) which was derived in Section I-D-1; the velocity is proportional to the steam condensation rate. Particle removal would occur according to Eq. (52), derived in Section I-E which is repeated here;

$$\log N/N_o = -730W \tag{52}$$

The symbols have the same definition as above. Values calculated from Eq. (52) are plotted on Fig. 16 as the line labeled "thermophoresis".

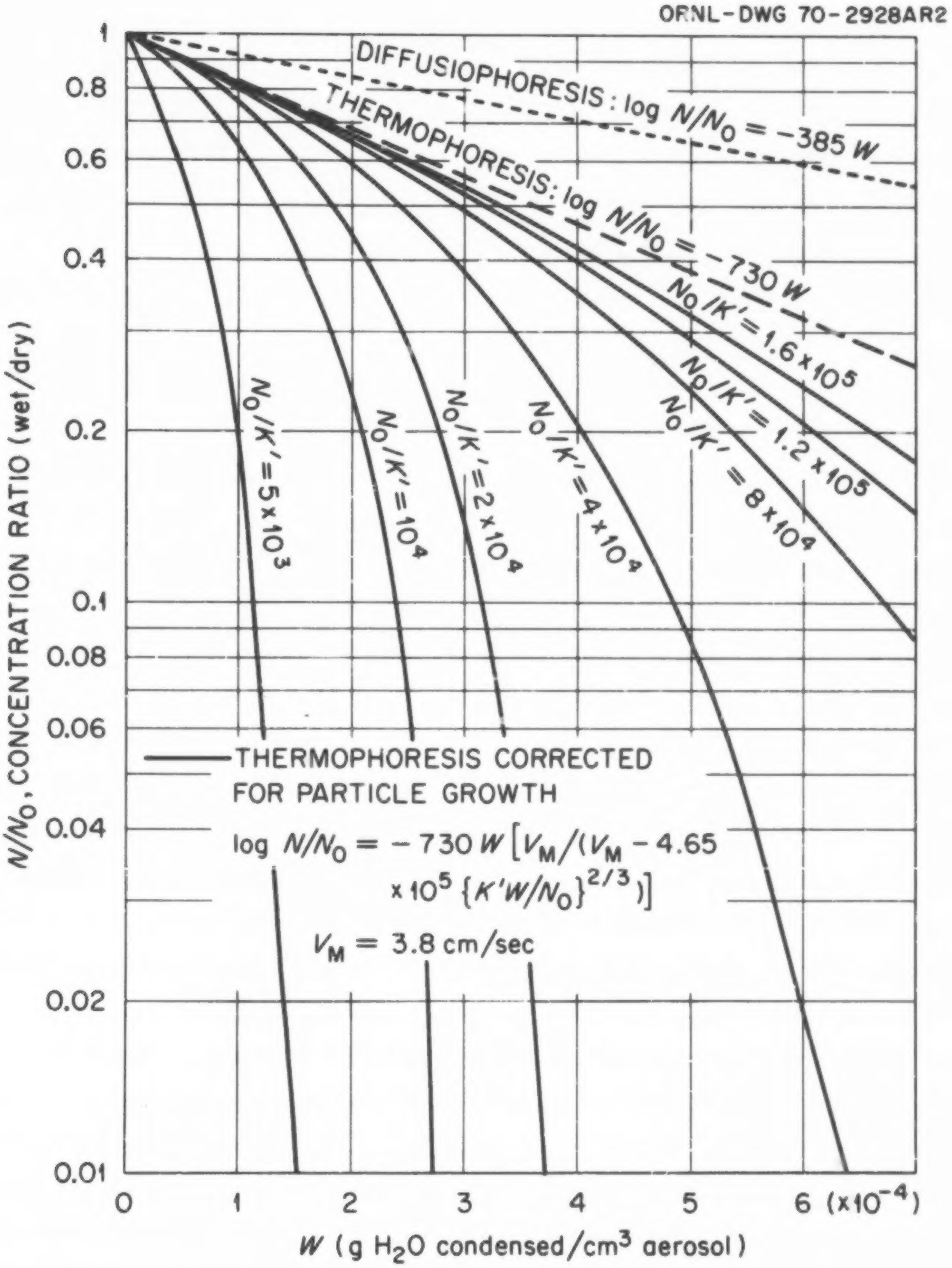

Figure 16. Theoretical Increase in Removal Efficiency Due to Growth of Hygroscopic or Hydrophillic Particles.

We have now to consider particle growth. If the water condenses on the particles, thermophoresis is the special deposition mechanism but in addition there may be enhanced deposition due to the particle growth. We have predicted that one consequence of growth by condensation is that further growth by turbulence becomes likely as described in section I-D-2. We endeavored to simplify the interpretation of our experiment by minimizing growth due to turbulence. This was done by avoiding sharp bends in the outlet and by means of the heated and screened section near the bottom of the tube (see Fig. 15); this tended to reduce the turbulence associated with the inlet streams prior to condensation. We also ran the experiments at a low velocity (3.8 cm/sec). This flow rate was something of a compromise; it is a low velocity but high enough to enable us to have a volume flow of 16.5 liters/min which, in turn, enabled us to use the electrostatic particle counter (which uses 28 liters/min of sample) with only a modest dilution with air. So our treatment of growth due to turbulence was to try to avoid it; this of course will reduce the removal efficiency of the device but hopefully will allow a more confident interpretation of the data. In one special series of tests the velocity was varied to briefly explore that variable, but all other tests were at 3.8 cm/sec.

Now to consider the effects of the growth that may occur due to condensation. To introduce this topic more directly, we wished to design the experiment (i.e., to modify Goldsmith's experiment) in such a way that the results - the removal efficiencies - would depend in some simple and predictable way on growth. We proposed to accomplish this with upward flow (rather than downward as in Goldsmith's experiments). With upward flow the grown particles will tend to fall (due to gravity) against the upward draft, they will therefore reside in the condenser longer, suffer the thermophoretic velocity longer and be more apt to get caught. It was necessary for the upward velocity to be low. The 3.8 cm/sec upward velocity used is very large compared to the falling velocity of a unit density sphere (such as a water droplet) of 2 microns diameter (i.e., 0.01 cm/sec). A 5 micron drop falls at 0.1 cm/sec which might be significant with respect to 3.8 cm/sec. A 10 micron drop falls at 0.3 cm/sec, a 15 micron drop at 0.7 cm/sec, a 20 micron drop at 1.2 cm/sec; these sized drops would reside significantly longer and their removal efficiency should be significantly higher than that for smaller particles.

We need now to make quantitative prediction of the removal efficiency enhancement due to growth by condensation. As mentioned in Section I-D-2, we anticipated two possible growth patterns; one is that all the particles share the condensed steam equally (i.e., they all grow the same amount) and the second is that relatively massive growth accurs on favored particles, none on the others. We will first consider the case of equal growth of all particles. This will tend to be the situation (as described in Section I-D-2) with hygroscopic particles and possibly hydrophillic particles and at high water vapor supersaturation. As noted above, the effect of growth is to increase the residence in the condenser hence the time during which the particle is subjected to the thermophoretic force toward the wall. The place that residence time appears in the formulation was noted with respect to Eq. (46)(in Section E).

The relative increase in residence time (over that presumed if the particle is assumed to travel at the same velocity as the medium) is the velocity of the medium, say V_M, divided by the velocity of the particle which is V_M minus the Stokes Law settling velocity, i.e., $V_M - V_S$. As suggested in Eq. (46) this can be attached as a correction factor onto Eq. (52)(which appears above); hence:

$$\log N/N_o = - 730W[V_M/(V_M - V_S)]. \tag{53}$$

If the turbulence is insufficient to cause significant coagulation then the particle growth is due only to condensation of water and the settling velocity V_S can be related to the amount of water condensed. The settling velocity, V_S, is given by Stokes' Law, in terms of particle volume V,

$$V_S = \frac{\rho g\ V^{2/3}}{3(6\pi^2)^{1/3}\eta} = 4.65 \times 10^5\ V^{2/3} \tag{54}$$

where ρ the particle density (g/cm^3) is taken to be unity since most of the particle will be water, g is the acceleration due to gravity, 980 cm/sec^2, η is the viscosity of air, 1.8×10^{-4} g cm/sec and V is the particle volume in cm^3. If the particle is mostly water then the water condensed per particle is Vρg H_2O/particle. The total amount of water condensed in the apparatus, per particle, is given by the total water condensed, W g/cm^3, divided by the inlet particle concentration, N_o particles/cm^3, i.e., by W/N_o. If the fraction, K' of the water condensed, condenses on particles then the water condensed per particle is $K'W/N_o$, hence:

$$V\rho = K'W/N_o \tag{55}$$

and from Eq. (53):

$$V_S = 4.65 \times 10^5 \, (K'W/N_o)^{2/3} \tag{56}$$

If we substitute Eq. (56) into Eq. (52),

$$\log N/N_o = - 730W \, [V_M/(V_M - 4.65 \times 10^5 [K'W/N_o]^{2/3})]. \tag{57}$$

In our condenser the value of V_M was 3.8 cm/sec. Calculated values according to Eq. (57), of N/N_o (the ratio of outlet to inlet concentration) are plotted vs W (steam condensation rate in g H_2O/cm^3 aerosol) for various values of N_o/K' on Fig. 16.

Recall that these N/N_o values are expected with hygroscopic and may be hydrophillic particles especially at high water vapor supersaturation under conditions where no turbulent growth occurs. In our experiments we expect minimal turbulent growth but the supersaturation will be low; hence we might expect this behavior for hygroscopic and may be for hydrophillic particles. The parameter K' will be something of an indicator of the validity of our assumptions; if K' is unity then all the water condensed on particles; if K' is less than unity some of the water condensed directly on the wall; K' would be greater than unity if significant growth due to turbulence occurred.

Let us consider the other growth pattern; massive growth of a fraction of the particles. Hydrophobic particles on being subjected to supersaturated water vapor will tend to resist adsorption of the first layer of water molecules (as noted in Section I-D-2). Some particles, in the group, just as a matter of chance, will be subjected to a higher supersaturation than the others, and the first layer of water will be forced onto these particles. Subsequent condensation can occur easily on these particular particles. These particles will therefore probably grow quite large and fall out. Presumably none of these favored particles will escape the condenser. At the same time the particles which have not grown are subjected to thermophoresis and are swept toward the wall according to Eq. (52).

A similar behavior might occur with hydrophillic particles at very low supersaturation. In order to arrive at a simple, quantitative description of these processes, let's assume that the condensation on the particular particles occurs and these particles fall; after that process is over we will assume that the thermophoresis sweep begins. This infers that the number concentration of particles near the bottom of the condenser where thermophoresis begins is not N_o (the inlet concentraton) but N_o-N' where N' is the reduction in number concentration due to massive condensation on favored particles. We might expect the fraction of the particles which grow, N'/N_o, to be linearly dependent on the supersaturation which (other things being equal) should be proportional to W the amount of steam condensation (g H_2O/cm^3 aerosol). In other words we are suggesting that if we double the amount of steam condensation that we will double the fraction of favored particles on to which water condenses. Hence:

$$N'/N_o = KW \qquad (58)$$

where K is an incompletely defined constant with units of cm^3 of aerosol per g of water condensed. It follows that the inlet concetration for thermophoresis, $N_o - N'$ is

$$N_o - N' = N_o(1 - KW). \qquad (59)$$

The term N_o in Eq. (52) is the number concentration before any removal by thermophoresis; so for this growth pattern N_o should be replaced by the expression for N_o-N' in Eq. (59) to give:

$$\log N/N_o = - 730W + \log (1 - KW). \qquad (60)$$

An alternative to Eq. (60) might be applicable as follows. If the number concentration N_o is very high then the fraction of particles which grow might be less than if the number concentration is low. In other words, at high concentration Eq. (58) might fail; the number of particles which undergo massive growth, N' (rather than the fraction which grow, N'/N_o) might be proportional to W, hence K in Eq. (58) would become

$$K = K''/N_o \qquad (61)$$

for high values of N_o. Proceeding with the derivation as before:

$$\log N/N_o = - 730W + \log (1 - K''W/N_o). \qquad (62)$$

If it is assumed that:

$$K = 3 \times 10^3 \qquad (63)$$

that Eq. (59) applies for N_o less than 10^4, that:

$$K'' = 4 \times 10^7 \tag{64}$$

and that Eq. (62) applies for N_o greater than 10^4, then the N/N_o values would vary with W and N_o as shown on Fig. 17. (The values of K and K" and the critical concentration of 10^4 particles/cm^3 are the particular values which will later be shown to fit data.)

Recall that the N/N_o values on Fig. 17 are expected to be obtained with hydrophobic particles especially at low supersaturation. They may apply, perhaps with modified values of K, K" and critical concentration, for hydrophillic particles especially at low supersaturation.

To recapitulate, the major objective is to distinguish on the basis of experimental results first whether the water condenses largely on particles or on the cold walls. We expected to do this on the basis of removal efficiencies (i.e., by distinguishing between the thermophoresis and diffusiophoresis curves on Figs. 16 and 17) and also by direct observation of increase in particle sizes. We will deduce what we can in order to distinguish between the possible growth patterns in terms of removal efficiencies (i.e., by comparison of observed N/N_o values with those on Figs. 16 and 17).

C. Aerosol Counting and Sizing

The following system of instruments were used as required to analyze the effluent from the condenser. There was a condensation nuclei counter[31] (CNC) which indicates total number concentration, an electrostatic particle counter[37] (EPC) which indicates number concentration in each of a succession of 15 diameter increments from 0.015 micron to 1 micron, and an optical counter[33] (OPC) which indicates number concentration in each of 12 particle diameter increments from 0.3 to 8 microns. A computer code was available to convert the data from these instruments to computer plots of size distribution. (Examples of these plots are shown later.)

D. Aerosol Generators and Test Aerosols

A commercially available generator[34] was used to generate latex particle aerosols. Three sizes of latex beads were employed: 1.857, 1.099, and 0.500 micron mean diameter. To demonstrate the size distribution each aerosol was fed into the condenser at a rate of 2 liters/min, diluted with 16.5 liters of air (and no steam). The effluent was analyzed with the

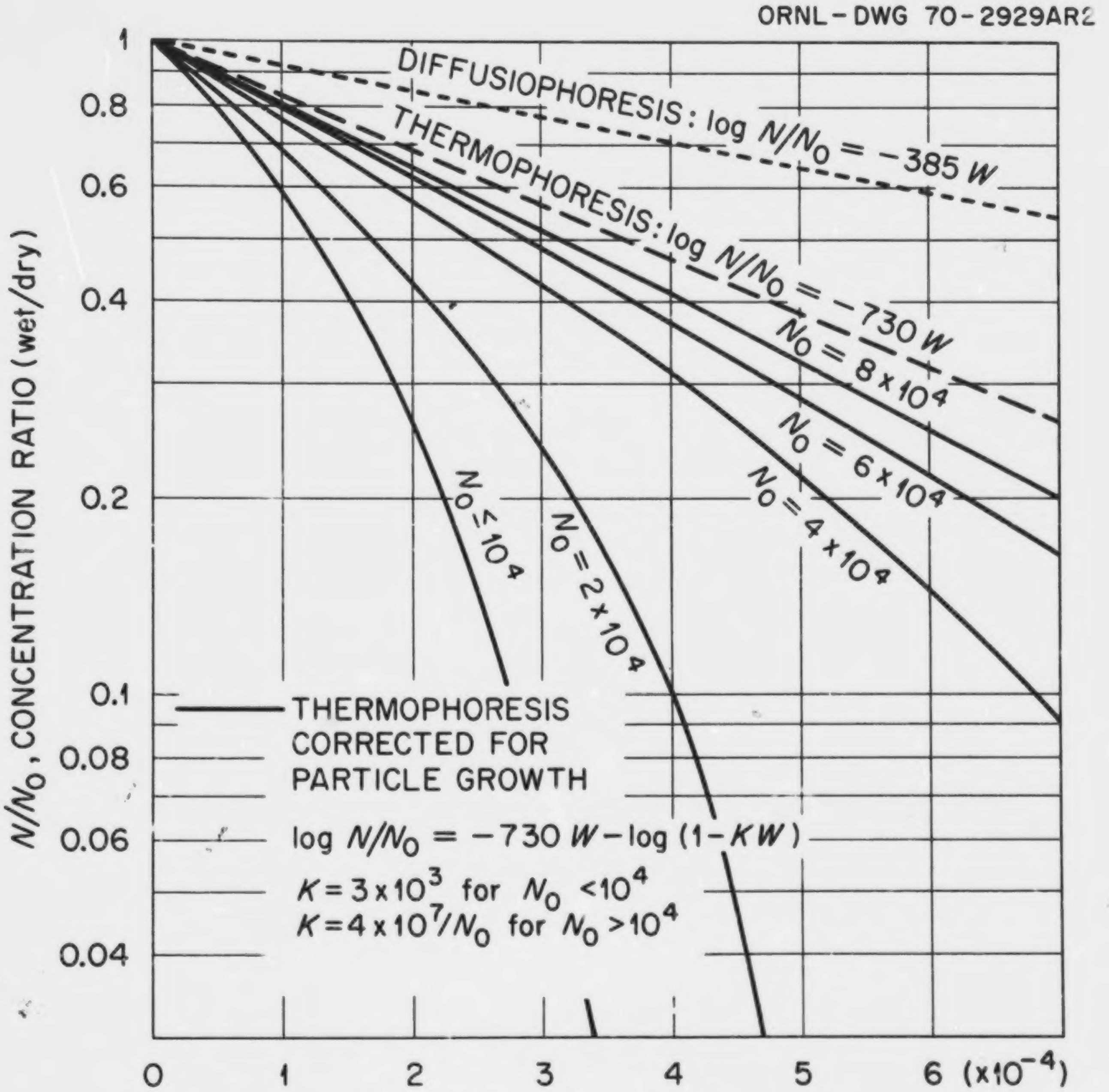

Figure 17. Theoretical Increase in Removal Efficiency Due to Growth of Hydrophobic Particles.

particle sizing instruments and the data converted via computer to the size distribution plots shown in Figs. 18, 19, and 20. These are plots of volume fraction distribution function vs particle volume. Volume fraction is a convenient measure of concentration; it is the volume of particles per unit volume of aerosol and is indicated by the symbol PHI. The volume fraction distribution function, d(PHI)/dV (or dØ/dV), which is the change in volume fraction with particle volume is plotted on the ordinate. The maximum in the distribution occurs at the volume fraction or mass mean particle volume. The mass mean diameter is also noted on the figures. Also the observed number concentration, n (from the condensation nuclei counter) is listed on the figures. The total volume fraction concentration, Ø (from the computed integral under the observed volume fraction distribution values over the particle volume range) is also listed as is the mass concentration M, which is simply Ø times the particle density. Note that these distributions and concentrations are for the highest concentration tested; three other concentrations: 3/4, 1/2 and 1/4 of these values were also tested. Note also that latex is a plastic substance; it is hydrophobic.

A DOP (dioctylphthalate which is a hydrophobic oil) aerosol generator from an available design[35] was employed. This generator uses a solution of dioctylphthalate in alcohol as feed material. An atomizer generates fine droplets of the feed solution; these droplets are vaporized in a section of a vertical quartz tube. Each droplet vaporizes down to a nucleus of non-volatile impurity. Controlled condensation then takes place to reform the droplets, each of nearly the same size. The average droplet diameter is varied by changing the concentration of DOP in the feed solution; four particle sizes were studied. As with the latex beads, the dry aerosols were analyzed for size distribution and concentration; two liters per min of feed aerosol was diluted with 16.5 liters of air into the bottom of the condenser (without steam) to yield the highest concentration of aerosol tested. The analyses are shown on Figs. 21, 22, 23, and 24. for the aerosol of each particle size. Both the EPC (electrostatic particle counter) and the OPC (optical particle counter) were employed. The total observed number concentrations are listed. The listed mass concentrations were measured by collecting particles from measured aerosol volumes on a filter and weighing. The listed volume fraction concentrations, Ø is the

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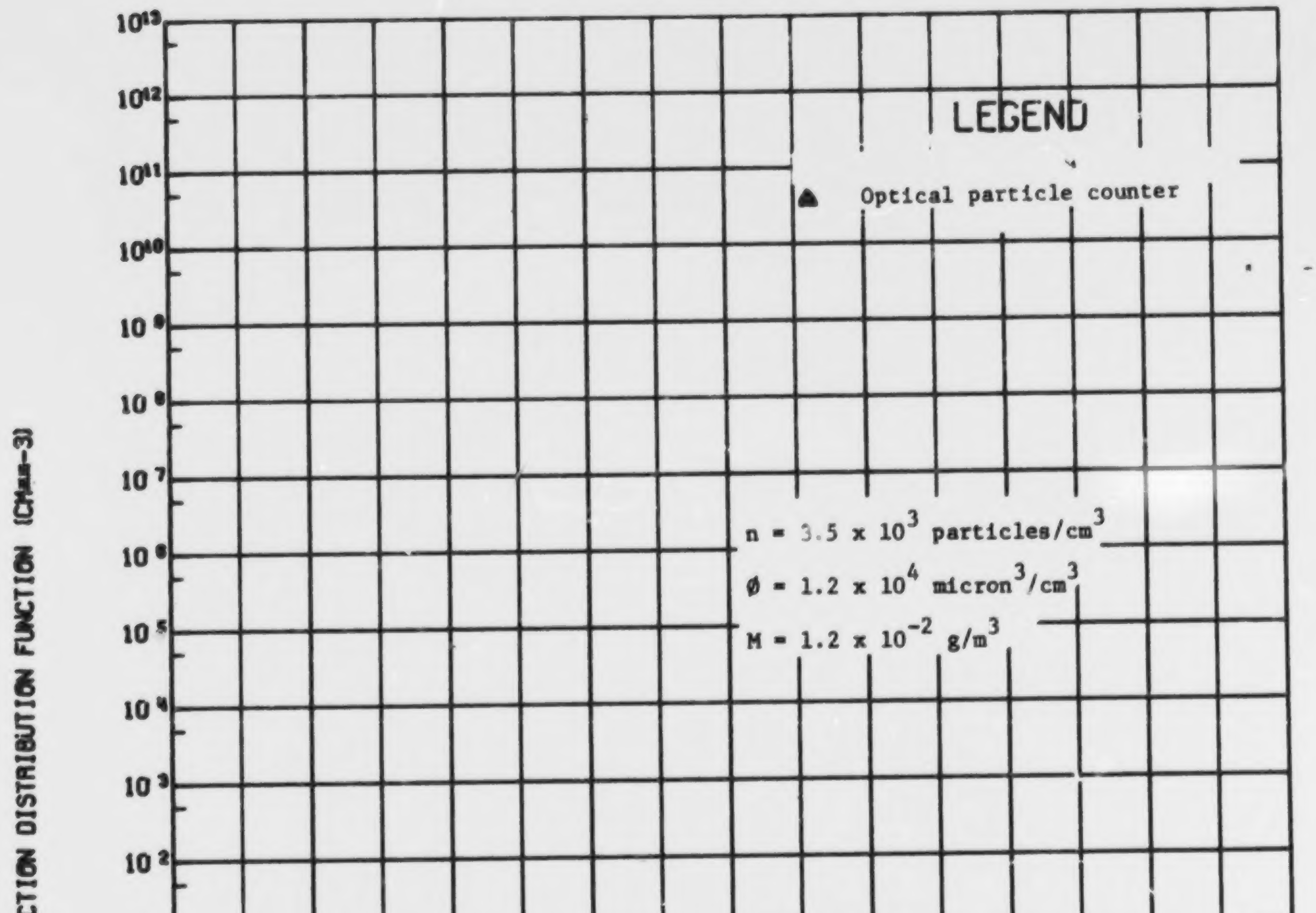

Figure 18. Latex, 1.9 Micron.

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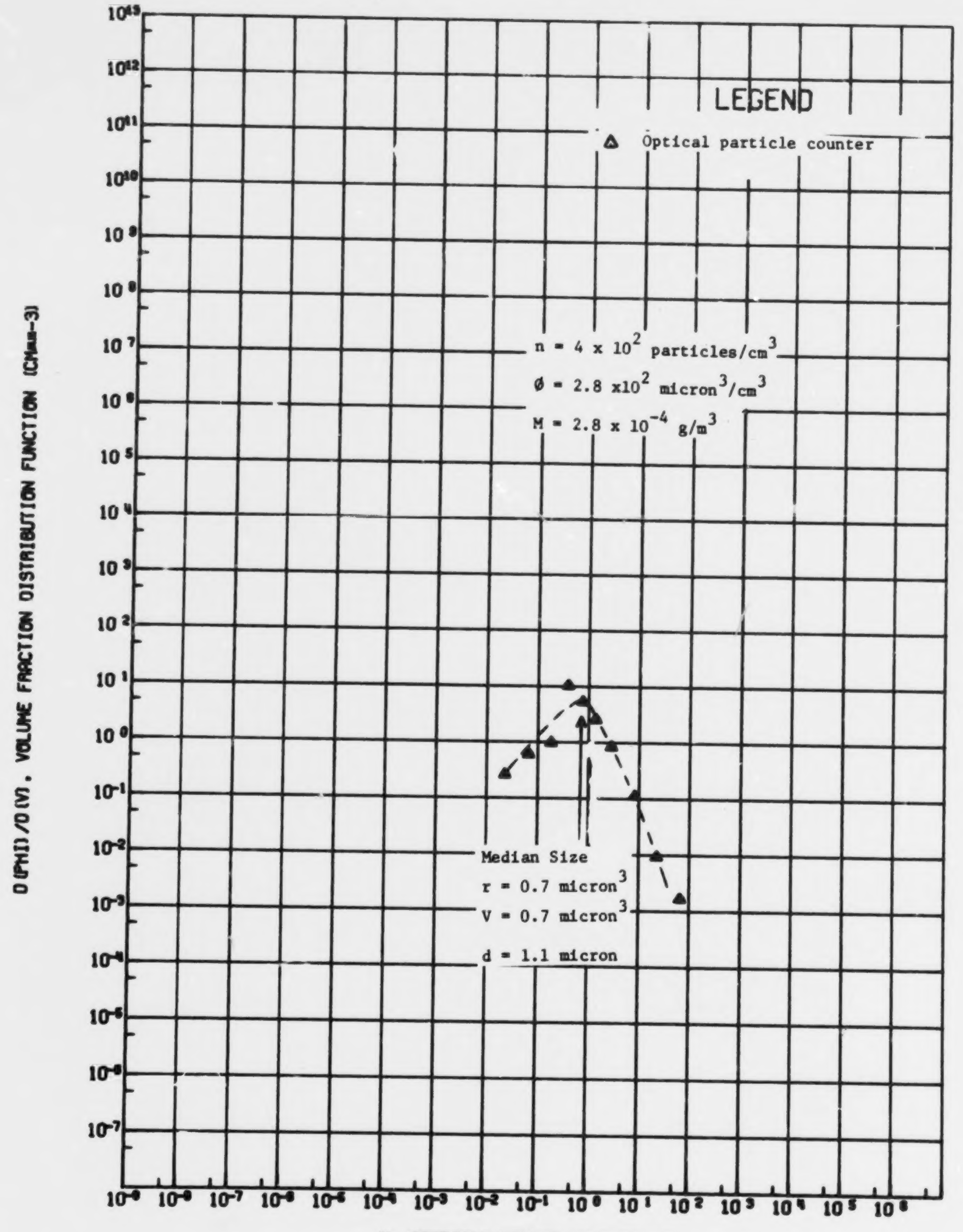

Figure 19. Latex, 1.1 Micron.

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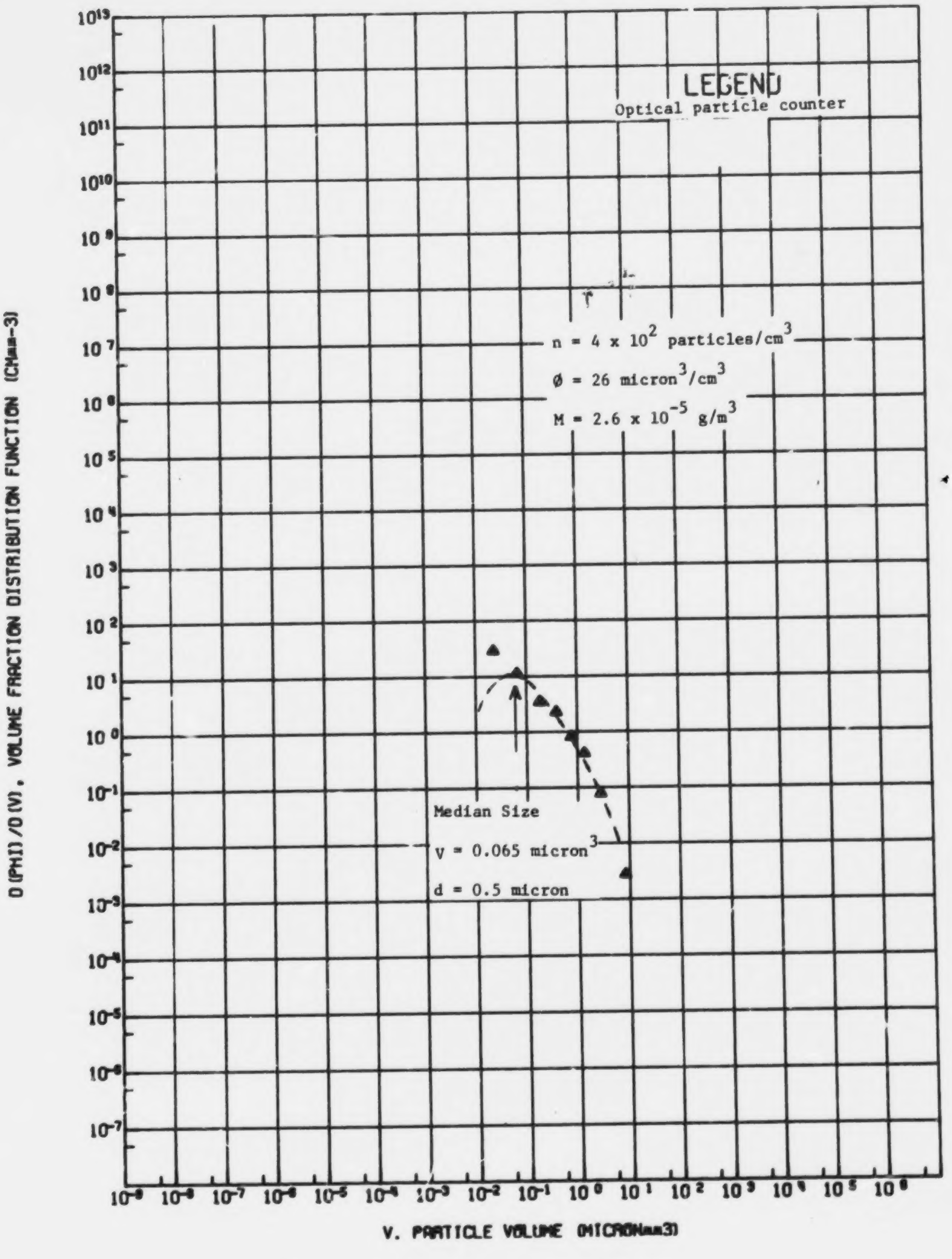

Figure 20. Latex, 0.5 Micron.

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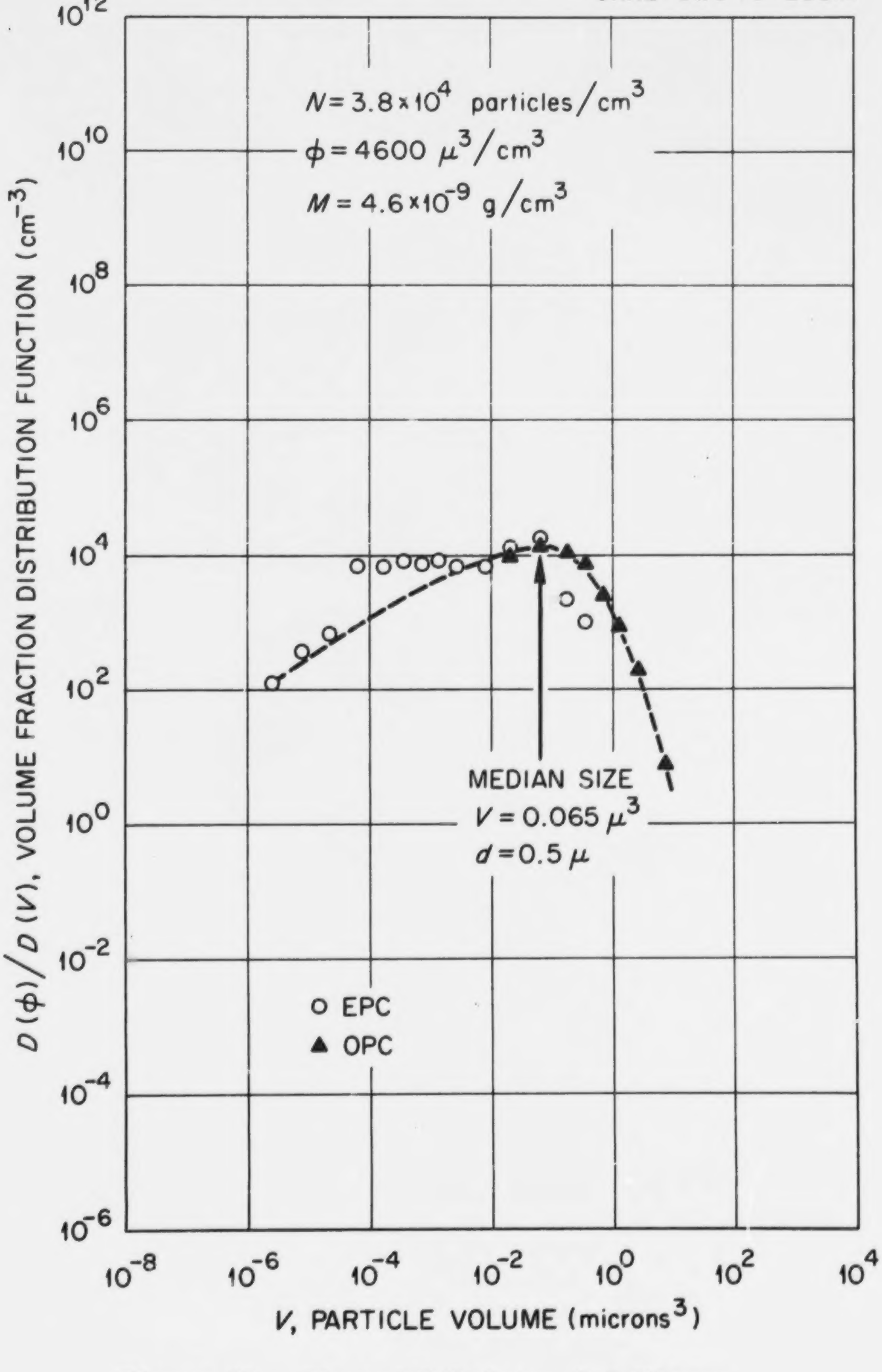

Figure 21. Dioctylphthalate, 0.5 Micron.

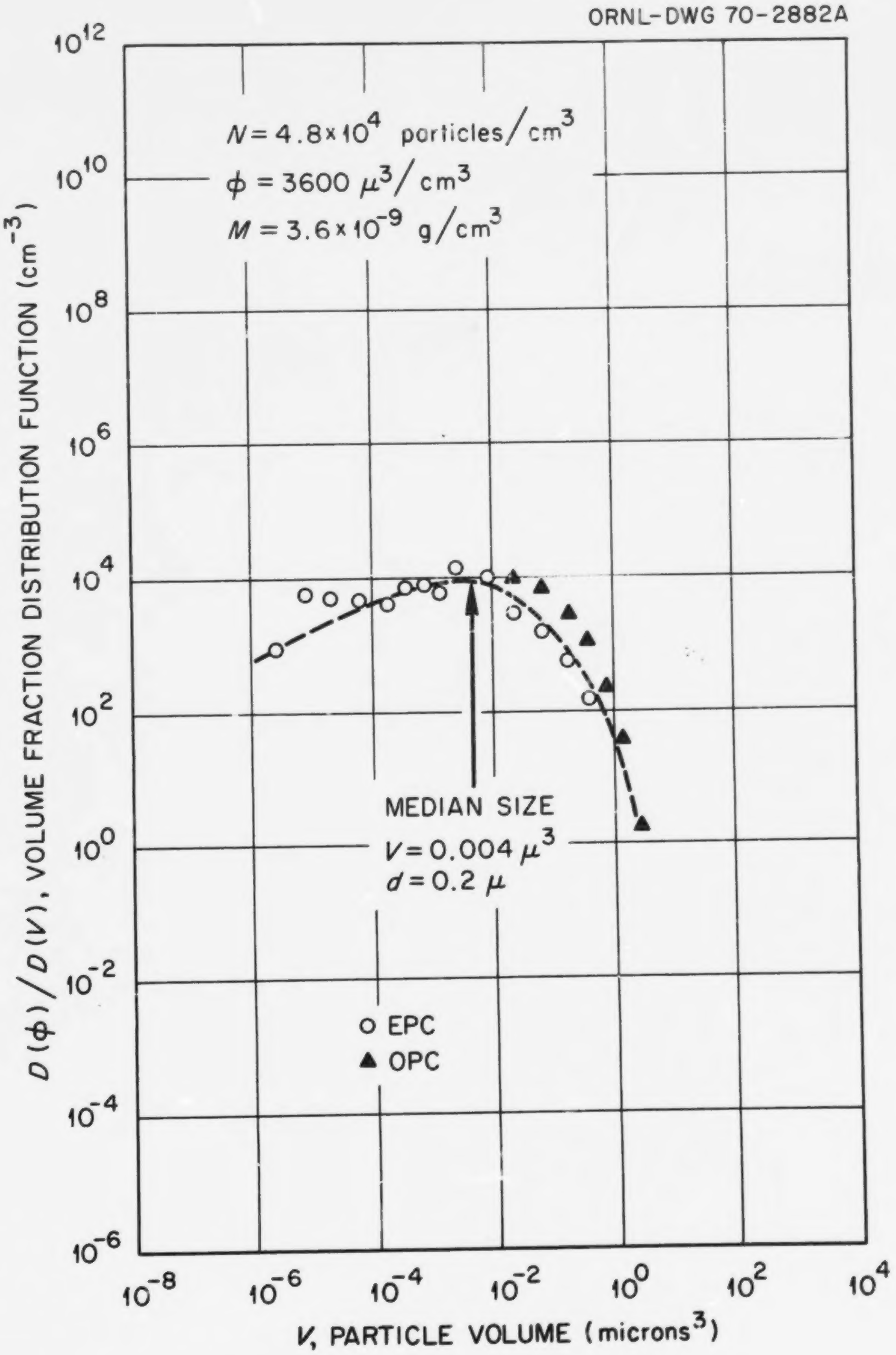

Figure 22. Dioctylphthalate, 0.2 Micron.

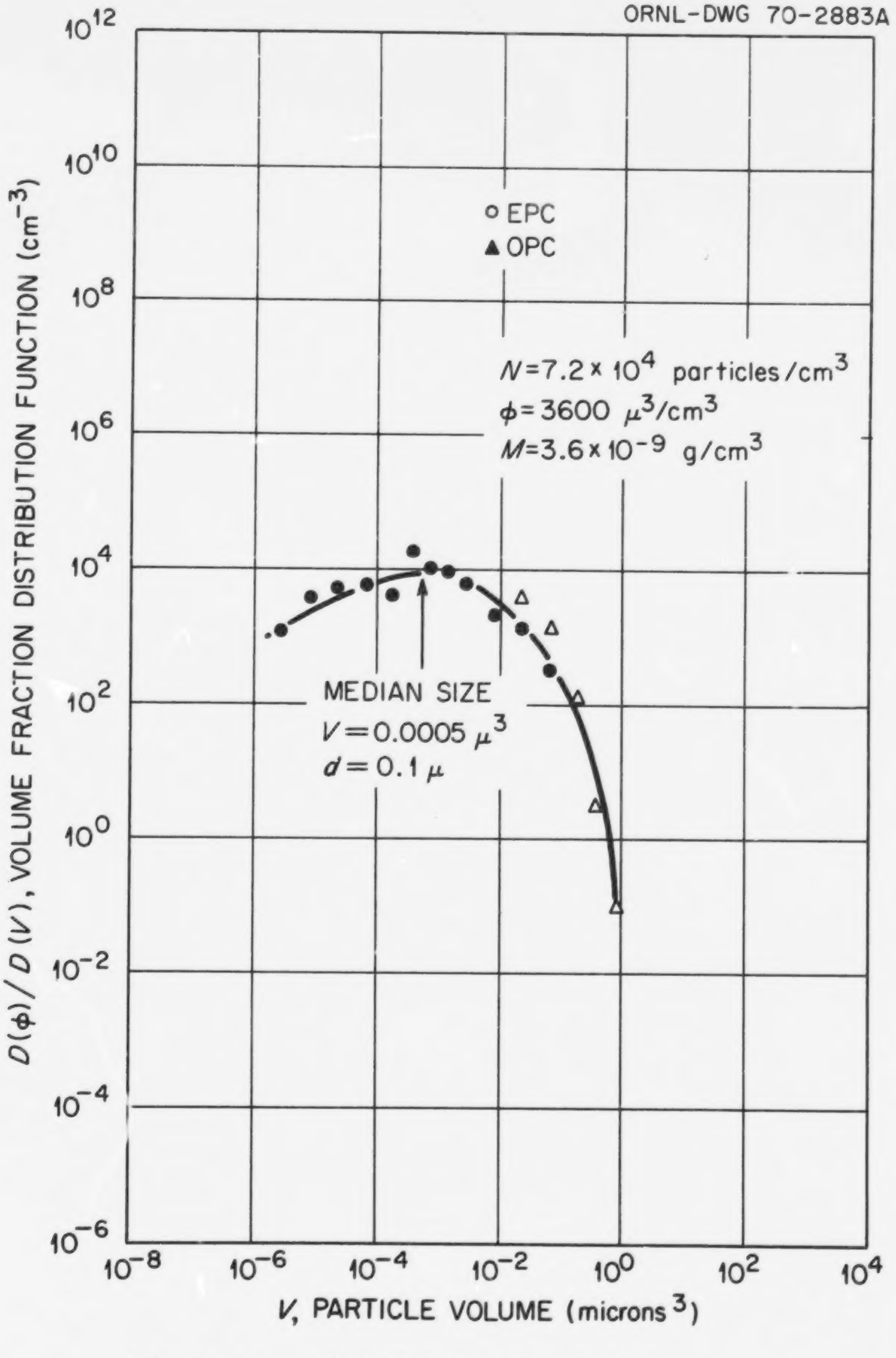

Figure 23. Dioctylphthalate, 0.1 Micron.

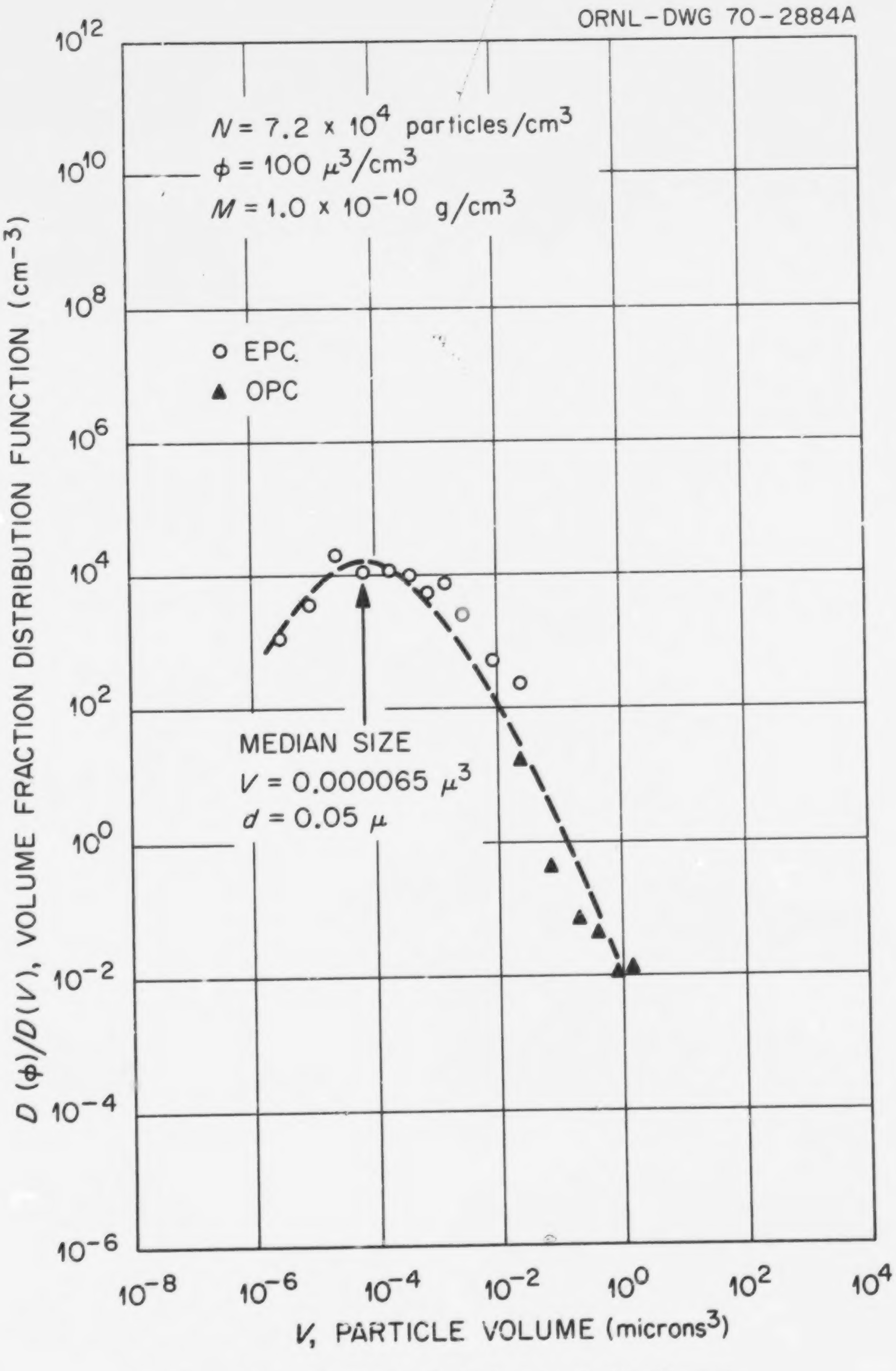

Figure 24. Dioctylphthalate, 0.05 Micron.

mass concentration divided by the particle density (about 0.96 g/cm^3). Note that the mean particle diameters were, respectively, 0.5, 0.2, 0.1, and 0.05 microns. Again note that four concentrations of each of these aerosols were tested; the data on Figs. 21-24 refer to the highest concentrations, the other concentrations were 3/4, 1/2, and 1/4 of these.

An electric spark between metals of interest was used to generate aerosols of agglomerate oxide particles of a wide size distribution. These aerosols have been studied and described elsewhere;[7,9,36] these aerosols are probably a good facsimile of industrial aerosols formed in electric arc furnace and other processes where vaporization of high melting substances occur. They are hydrophillic substances.

A stainless steel oxide aerosol of this kind was generated and fed directly into the condenser; this aerosol at the highest concentration studied (i.e., 2 liters per min of feed aerosol diluted with 16.5 liters/min of air) was characterized as shown on Fig. 25. The spark was set up across the axis of a 2-in. diameter glass pipe; the power source was a Tesla coil.

In previous work[7,9,36] we have developed the idea that the size distribution of such highly agglomerated aerosols is the result of a steady-state between coagulation (which makes big particles out of little ones) and settling (which preferentially removes big particles). We presume that the normalized number concentration distribution function, $[1/n][dn/dV]$ is proportional to the particle volume to the minus two, i.e., to V^{-2}. This assumption is based on both theory[37] (i.e., the theoretical development of the steady-state hypothesis) and on experimental data.[38] We also presume that the size spectrum goes from a sharply defined minimum size, V_{min} to a sharply defined maximum size, V_{max}. This second presumption seems commonly to be approximately true.[39] From these assumptions it can be shown that the number distribution function is:

$$dn/dV = (1/[V_{min}^{-1} - V_{max}^{-1}])\ n/V^2 \qquad (65)$$

and the volume fraction distribution function is

$$d\phi/dV = (1/\ln\ [V_{max}/V_{min}])[\phi/V] \qquad (66)$$

where n and ϕ are, respectively, the total number and total volume fraction concentrations.

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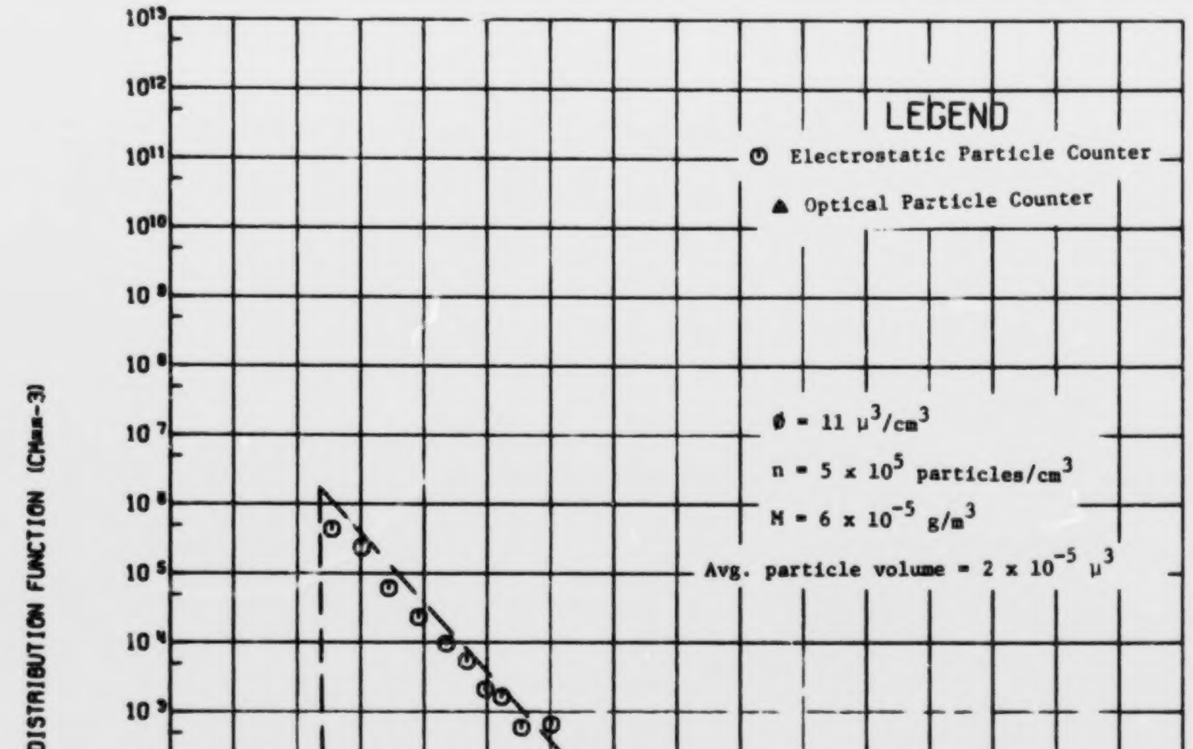

Figure 25. Stainless Steel Oxide, 0.007-15 Micron.

In these terms, the stainless steel aerosol described on Fig. 25 can be characterized by a volume fraction distribution function:

$$d\phi/dV = 0.5/V, \qquad (67)$$

and maximum and minimum particle volumes of about 2×10^3 cubic microns and 2×10^{-7} cubic microns. The minimum particle size is somewhat uncertain, because it is near the low end of the range of the instruments. The nature of these (highly agglomerated) aerosol size distributions is such that there are many more small particles than large ones and for approximate comparison one can take the minimum size (2×10^7 cubic microns in this case) as the (volume fraction or) mass median size. The corresponding particle diameter is about 0.007 micron. Alternatively, the average particle volume (the volume fraction divided by the total number concentration) can be used to characterize the aerosol. In this case the average particle volume was 2×10^{-5} μ. The number concentration is a measured value, the volume fraction is the computed integral of the distribution function over the particle volume range. The mass concentration is the volume fraction times the particle density (5.35 g/cm^3).

A second stainless steel oxide aerosol was produced in the electric spark using the high frequency starter attachment on a welding machine as the power source, with an air flow past the spark of 3.3 liters/min. In this case the aerosol was led into a plastic bag of about 10^5 cm^3 volume to allow further coagulation (and presumably larger average agglomerate particle sizes). Aerosol was led from the bag to the condenser experiment. Figure 26 characterizes this aerosol. Two liters of the feed aerosol were diluted with 16.5 liters of air before analysis as in previous cases to simulate the highest of four concentrations tested. Notice, on Fig. 24 that the minimum particle size is larger (2×10^{-6} μ^3 corresponding to a diameter of about 1.6×10^{-2}μ).

An iron oxide aerosol (Fig. 27) and a chromium oxide aerosol (Fig. 28) were made by a procedure which was entirely similar to that just described for stainless (i.e., the aerosol described on Fig. 26). Again the highest of four concentrations later tested in the condenser experiment were characterized as shown in Figs. 25 and 26.

An ammonium chloride aerosol was generated by controlled mixing of NH_3 and HCl gases and aging in a plastic bag; i.e., an aerosol was

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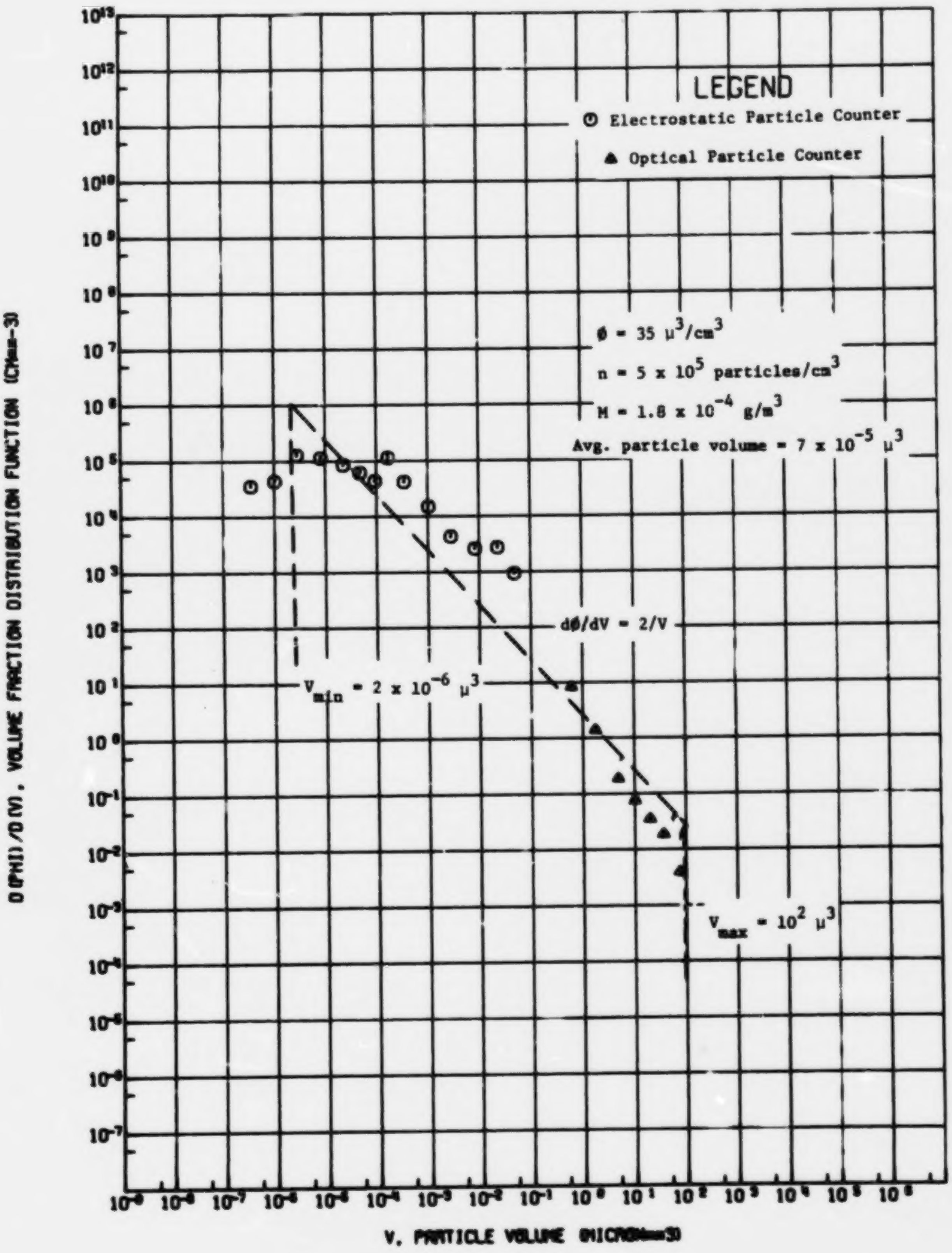

Figure 27. Iron Oxide, 0.015-6 Micron.

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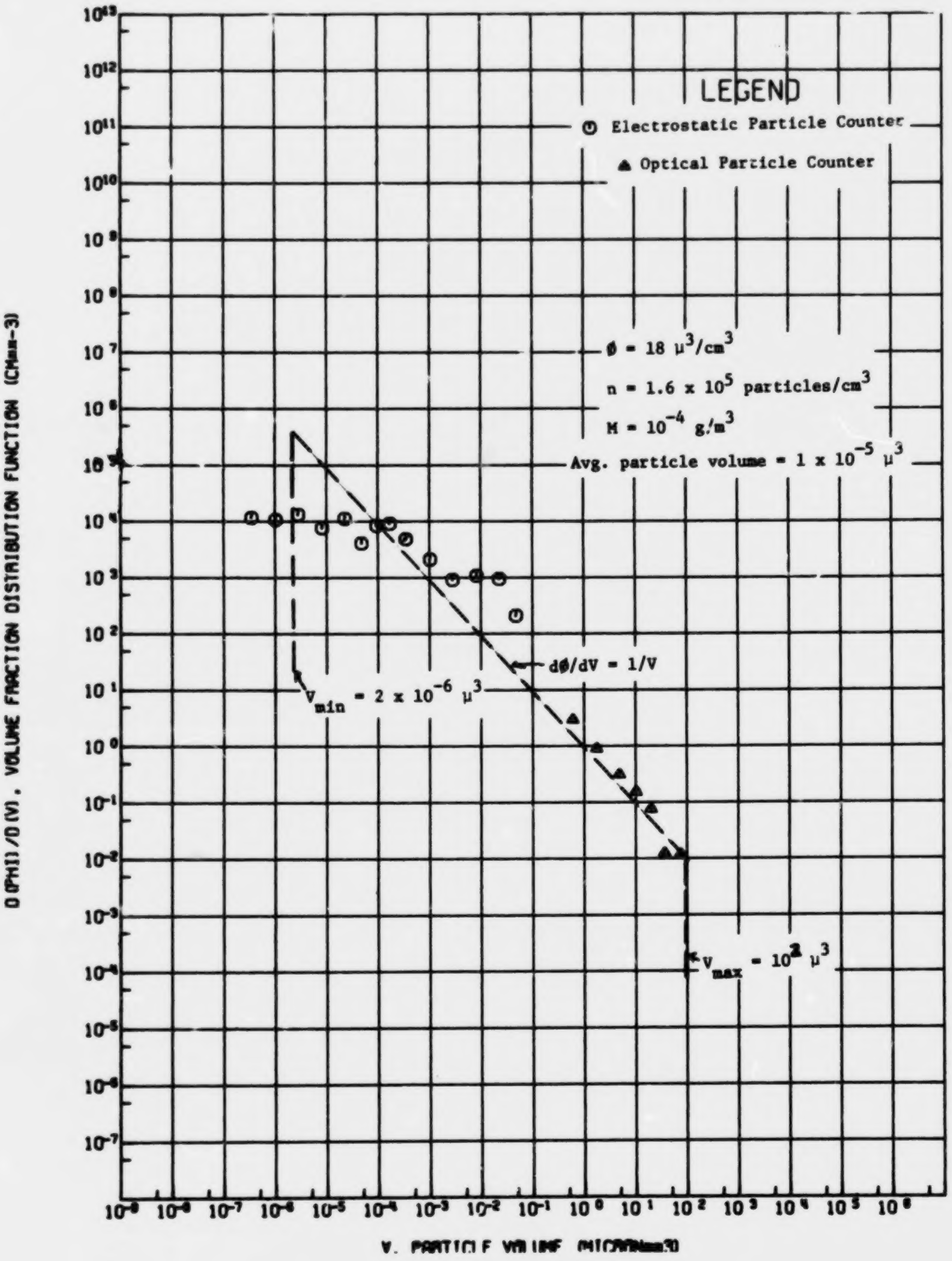

Figure 26. Stainless Steel Oxide, 0.015-6 Micron.

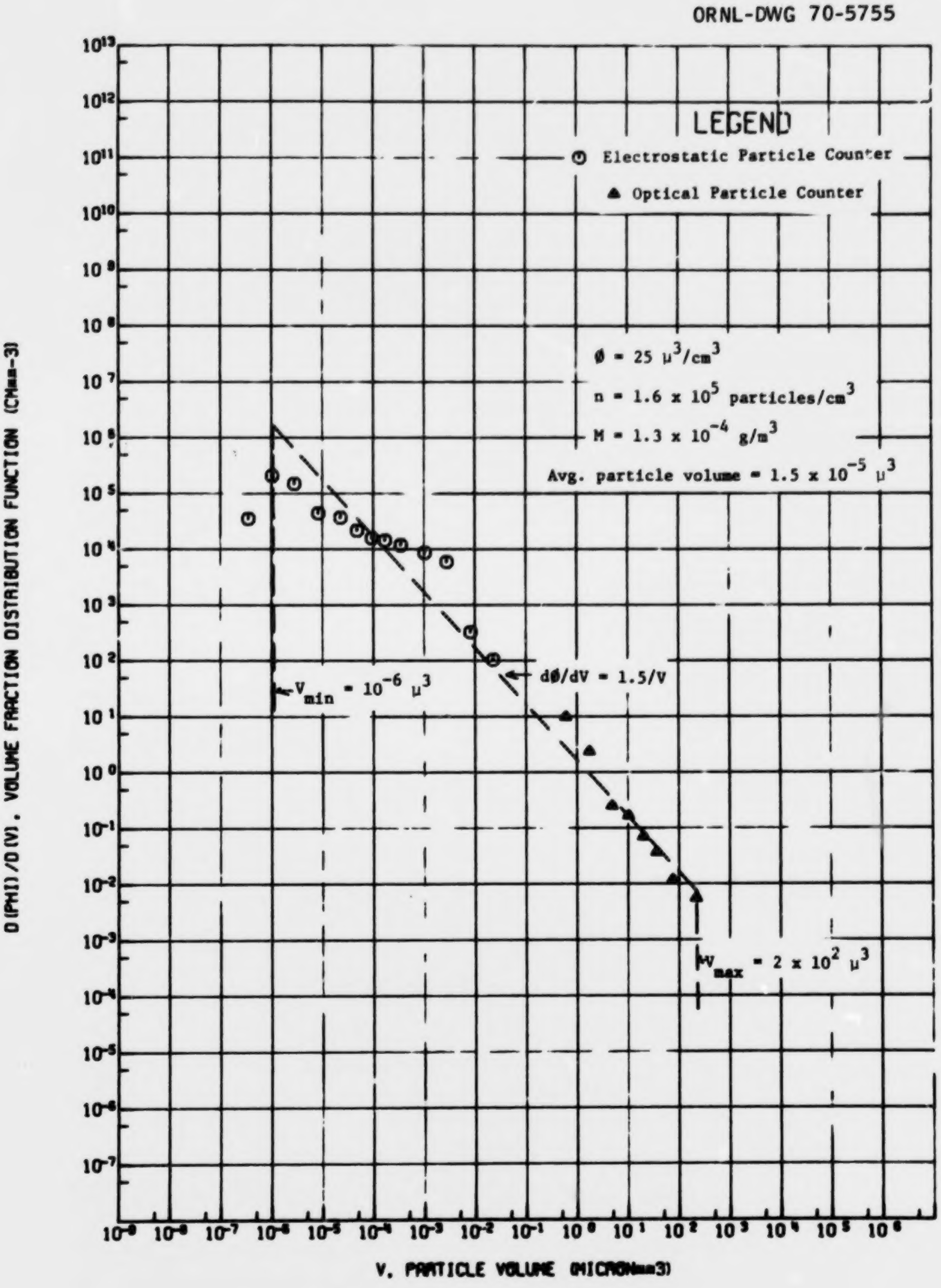

Figure 28. Chromium Oxide, 0.012-7 Micron.

continuously generated into the bag, some aerosol was continuously fed to the condenser and the rest was continuously discarded. The size distribution and concentration of the highest of four concentrations tested are shown on Fig. 29. Again the size distributions, and number concentrations are measured values, the volume fraction is the computed integral of the distribution function and the mass concentration is the volume fraction times the particle (NH_4Cl) density. Of course, ammonium chloride is a good example of a hygroscopic substance.

Finally we used a commercially available spinning disc generator[40] to generate methylene blue particles of narrow size range. Methylene blue is a hygroscopic dye. Three median diameter values were obtained; about 2, 2.7 and 4 microns. The size distribution and concentration are shown on Figs. 30, 31, and 32. Since the spinning disk generates very dilute aerosols, only one concentration of each particle size was tested, namely the highest concentration we could get with our test procedure (of 10.5 liters/min aerosol plus air and 8 liters/min of steam plus air). This was achieved by feeding 10.5 liters/min of the aerosol feed along with 8 liters/min of dry air (for the initial characterization on Figs. 30-32).

So Figs. 18-32 characterize the test aerosols. In all cases aerosols of the concentration indicated on the figures were tested in the condenser; in most cases four other concentrations, 3/4, 1/2, and 1/4 of the highest value, were also tested. These aerosols cover a considerable range: 0.05 to 2 micron diameter hydrophobic, narrow size range particles, an assortment of wide size range, hydrophillic, metal oxide particles; a small particle, wide size range and 2-4 micron diameter narrow size range hygroscopic particles.

V. Data and Results

The condenser experiment (Fig. 15) was described above. It was noted that the total air flow up the condenser was,in all experiments, 16.5 liters per minute. For each test aerosol, the aerosol feed rate was varied and the steam feed rate was also varied. In each experiment the concentrations were measured without steam (cold and dry) then steam was added and after a time the concentrations were again measured. The outlet temperatures were close to room temperature.

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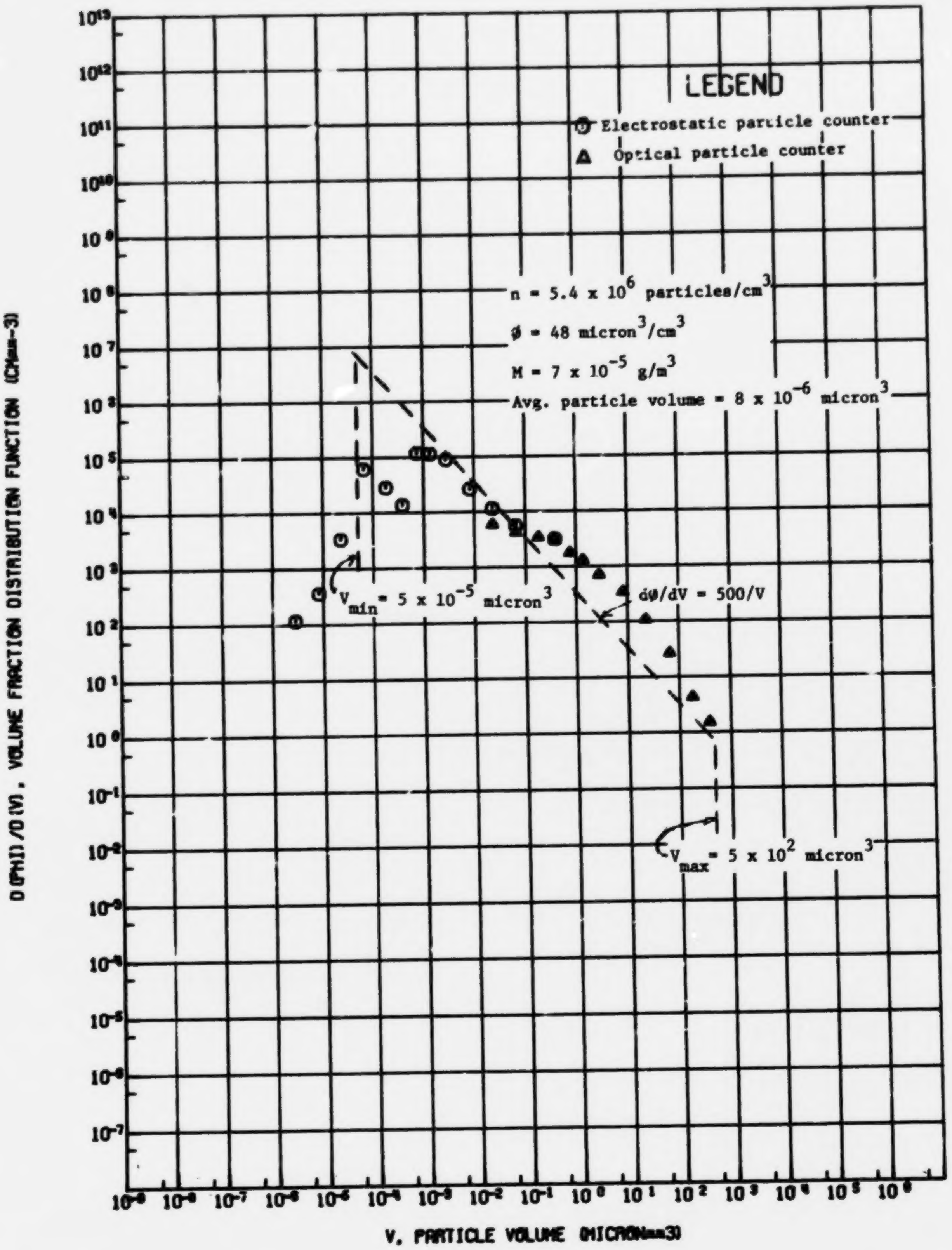

Figure 29. Ammonium Chloride, 0.06-13 Micron.

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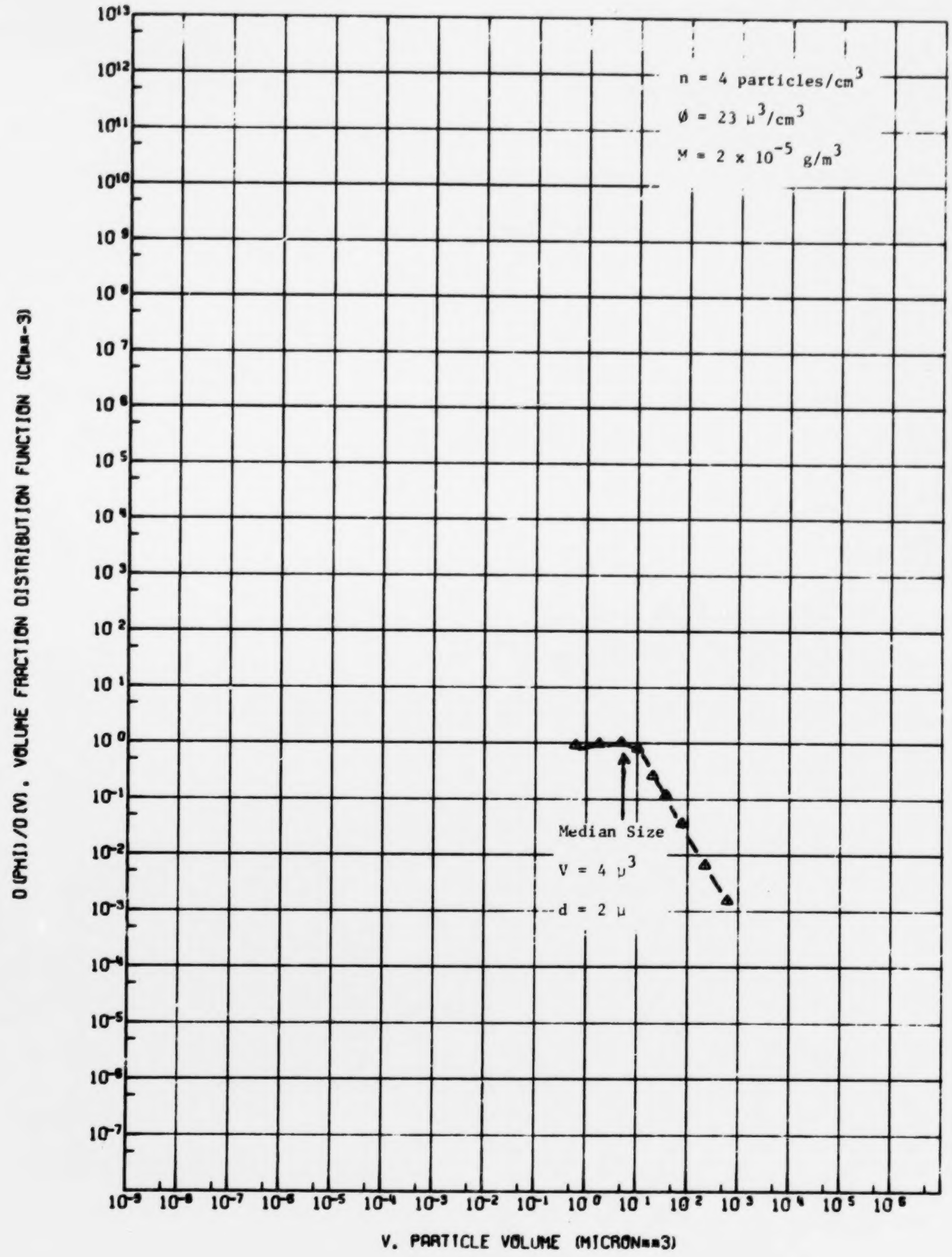

Figure 30. Methylene Blue, 2 Micron.

ORNL-DWG 70-10323

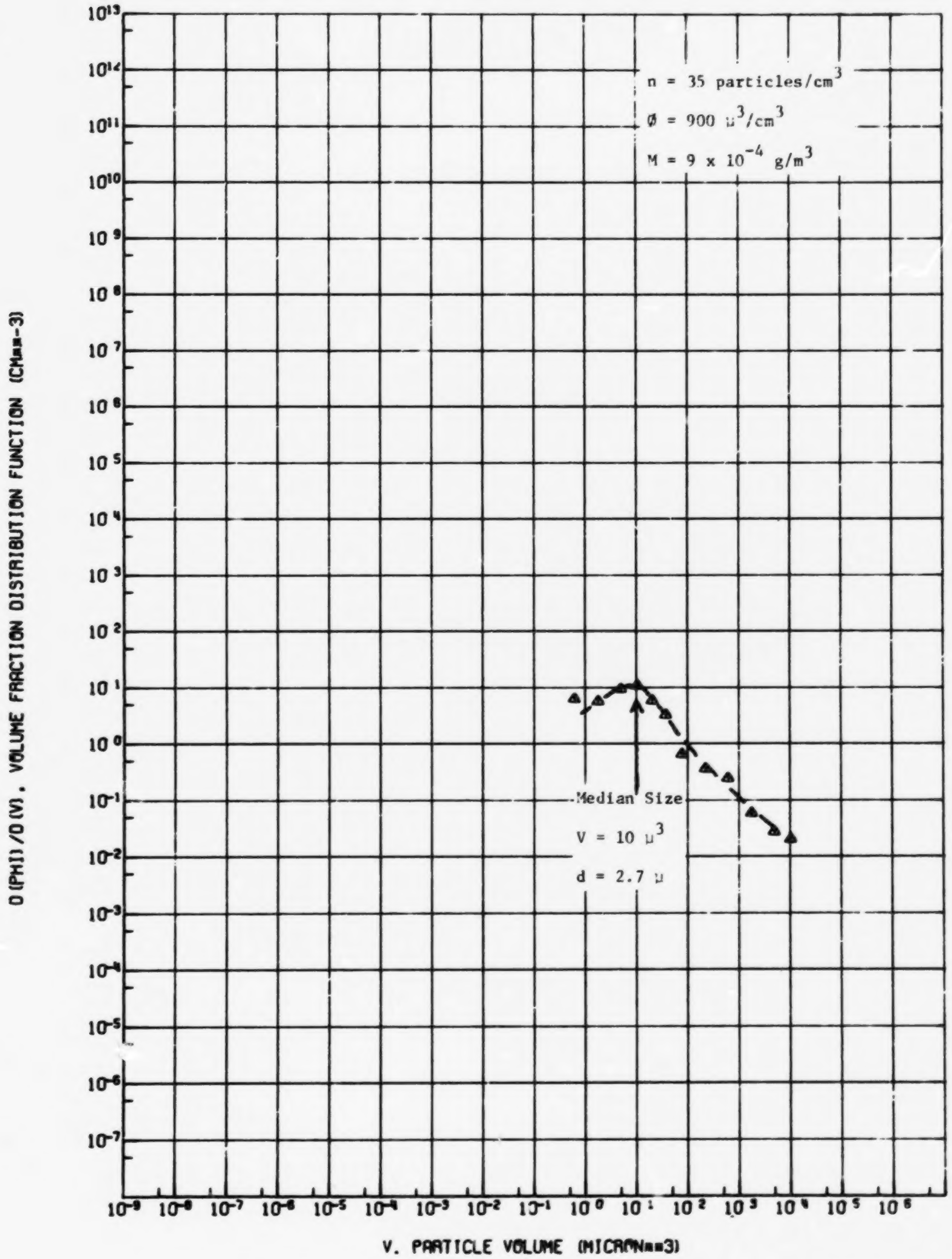

Figure 31. Methylene Blue, 2.7 Micron.

ORNL-DWG 70-10322

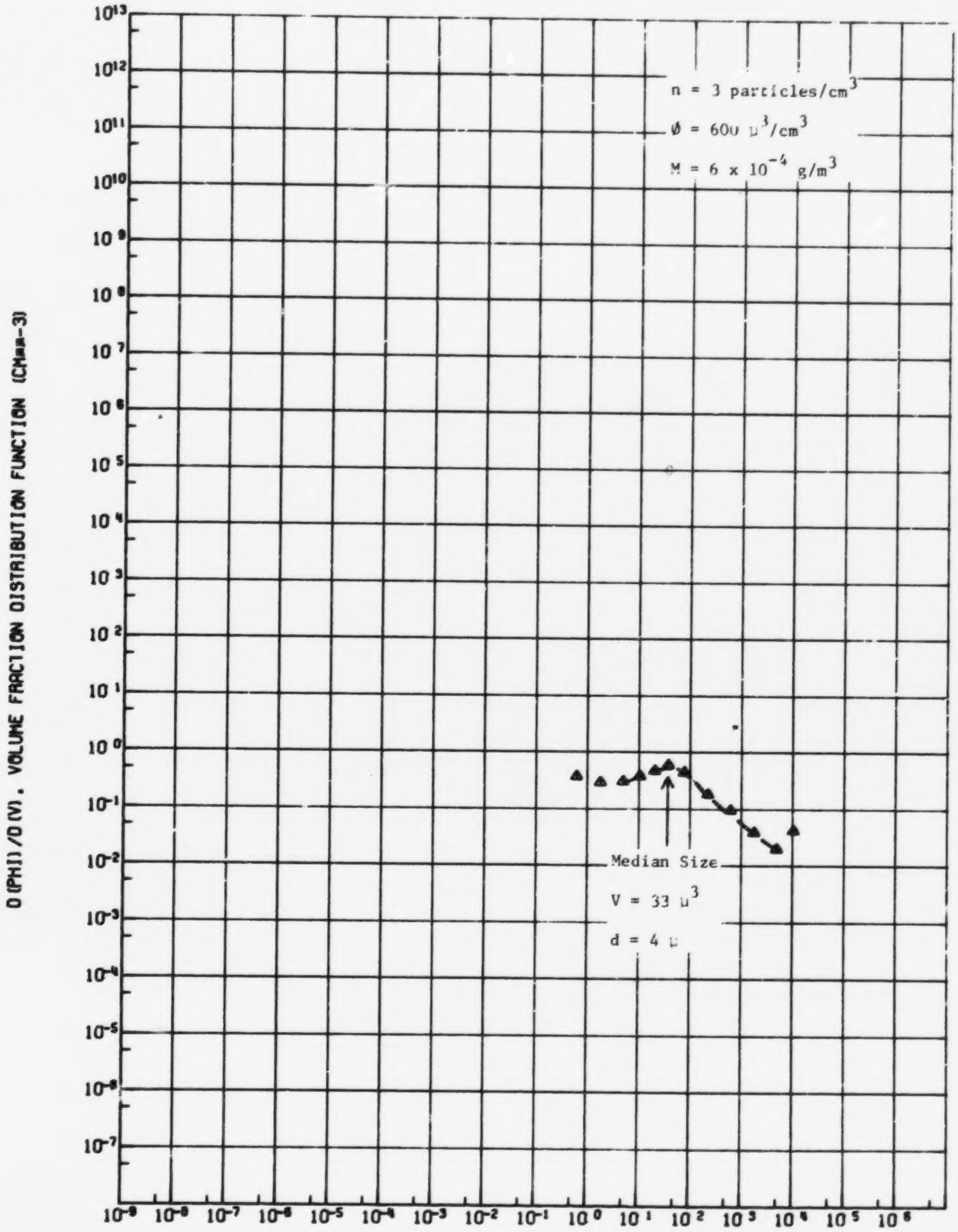

Figure 32. Methylene Blue, 4 Micron.

The data for each experiment consists of total aerosol number concentration, in some cases the mass concentration and the number of particles in each of a succession of particle size increments. There are always two sets of data; one for the wet run and one for the dry control run.

The data were processed via a computer code, which has been written by us to yield, first of all, a listing of data. An example of such a list is shown in Table 1 (for the stainless steel oxide aerosol characterized on Fig. 26 at 11.5 g H_2O/min steam feed rate). The number concentrations are listed first. The first line gives the concentration as measured by the CNC (i.e., by the condensation nuclei counter) for the dry, control run, then for the wet run and finally the ratio of the wet concentration to the dry one is given. Next the number concentrations from the OPC (optical particle counter) are given. These values are the sums of number concentrations in each particle size increment over the range of measurement of the optical counter (0.3 to 8 microns diameter). Then the number concentration from the EPC (electrostatic particle counter) are listed. These values are also sums of number concentration of particles in all size ranges within the range of the instrument (0.015 to 1 micron diameter).

The next group of data are total volume fraction concentration. The "makeup" value for the dry aerosol is calculated from the known mass concentration of the aerosol produced by the generator and the dilution involved in the experiment. The mass concentrations of the output of the generator is measured in separate experiments by collecting material from a known aerosol volume on a filter and analyzing. The next line in the table gives the volume fraction concentration obtained from the OPC (optical particle counter) data. These are obtained by taking the number of particles in each size range, multiplying by the volume per particle and then summing these volumes over the whole size range of the instrument. Similarly, the volume fraction from EPC (electrostatic particle counter) data is obtained.

There are two particle size distributions (for each the dry and wet aerosol); one is the number concentration distribution and the other the volume fraction concentration distribution. The particle counters give directly, the number of particles in each of a series of size ranges. The

TABLE 1

```
SS OXIDE, SPARK, 2.0 L/MIN FEED, 11.5 G H2O/MIN.

NUMBER CONC.(NO/CM**3)       DRY          ****G H2O/MIN   WET/DRY

     FROM CNC             0.170E 06     0.520E 05       0.306E 00

     FROM OPC             0.845E 01     0.747E 02       0.884E 01

     FROM EPC             0.525E 06     0.194E 06       0.370E 00

VOLUME FRACTION CONC.(MU**3/CM**3)
     FROM MAKEUP          0.227E 02

     FROM OPC             0.903E 01     0.104E 03       0.115E 02

     FROM EPC             0.929E 02     0.131E 02       0.141E 00

PARTICLE SIZE DISTRIBUTIONS

  VOLUME       NUMBER CONC. DISTRIBUTION          VOLUME FRACTION CONC.DISTRIBUTION
               DRY       11.5 GH2O/MIN WET/DRY    DRY       11.5 GH2O/MIN WET/DRY

  FROM EPC
  .351E-06     .277E 12 .776E 11 .280E 00         .290E 06 .811E 05 .280E 00
  .102E-05     .939E 10 .129E 11 .138E 01         .284E 05 .391E 05 .138E 01
  .281E-05     .472E 10 .315E 10 .667E 00         .395E 05 .263E 05 .667E 00
  .819E-05     .250E 10 .937E 09 .375E 00         .605E 05 .227E 05 .375E 00
  .225E-04     .482E 09 .126E 09 .261E 00         .322E 05 .841E 04 .261E 00
  .477E-04     .396E 09 .660E 08 .167E 00         .565E 05 .941E 04 .167E 00
  .933E-04     .143E 09 .338E 08 .237E 00         .397E 05 .941E 04 .237E 00
  .170E-03     .379E 08 .599E 07 .158E 00         .193E 05 .305E 04 .158E 00
  .351E-03     .163E 08 .279E 07 .171E 00         .170E 05 .292E 04 .171E 00
  .102E-02     .115E 07 .383E 06 .333E 00         .348E 04 .116E 04 .333E 00
  .281E-02     .784E 06 .270E 05 .345E-01         .655E 04 .226E 03 .345E-01
  .819E-02     .151E 06 .133E 05 .882E-01         .366E 04 .323E 03 .882E-01
  .225E-01     .156E 05 .156E 04 .100E 00         .104E 04 .104E 03 .100E 00
  .477E-01     .723E 03 .723E 03 .100E 01         .103E 03 .103E 03 .100E 01
  FROM OPC
  .607E 00     .433E 01 .309E 02 .714E 01         .781E 01 .558E 02 .714E 01
  .177E 01     .233E 00 .339E 01 .146E 02         .122E 01 .178E 02 .146E 02
  .485E 01     .107E-01 .267E 00 .250E 02         .155E 00 .386E 01 .250E 02
  .103E 02     .243E-02 .647E-01 .267E 02         .747E-01 .199E 01 .267E 02
  .201E 02     .662E-03 .555E-02 .837E 01        .398E-01 .334E 00 .837E 01
  .368E 02     .166E-03 .831E-03 .500E 01        .183E-01 .914E-01 .500E 01
  .758E 02     .171E-04 .342E-04 .200E 01        .386E-02 .773E-02 .200E 01
  .221E 03     .0        .0        .0              .0        .0        .0
  .607E 03     .0        .0        .0              .0        .0        .0
  .177E 04     .0        .0        .0              .0        .0        .0
  .485E 04     .0        .0        .0              .0        .0        .0
  .103E 05     .0        .0        .0              .0        .0        .0
```

number is taken and divided by the width of the size range (in particle volume units) to give $\Delta N/\Delta V$. These are the number concentration distribution values. For volume fraction distribution functions, the number in each size range is multiplied by the volume per particle for that size range (to give $\Delta\phi$, i.e., the increment of volume fraction) and this is divided by the width of the size range (in particle volume units). Hence we get $\Delta\phi/\Delta V$, the volume fraction concentration distribution value. The ratio of the values of $\Delta N/\Delta V$ and of $\Delta\phi/\Delta V$ of the wet to the dry aerosol cases are also listed.

The computer next supplies a graph of $\Delta N/\Delta V$ (or let's call it dN/dV) the number concentration distribution function vs particle volume, V. The distribution for both wet and dry cases are plotted as well as the ratio of wet to dry. An example (for the stainless steel oxide aerosol described in Fig. 26) of such a plot is given in Fig. 33. Similarly, $d\phi/dV$ vs V for wet and dry cases and the ratio of wet to dry values are plotted on another graph. An example is given in Fig. 34. These plots have been very valuable in spotting trends and generally keeping detailed account of the data. They are, however, too numerous to serve as a means of presenting results.

To demonstrate the particle size distribution results, families of curves of the kind shown on Fig. 33 and 34 labeled wet/dry were prepared. These are the ratios of the number or volume fraction distributions, ratios of the distribution found with steam condensation to the distribution found without steam condensation. The ratios of the number distributions and volume fraction distribution are identical (i.e., the wet/dry values on Fig. 33 are the same as those on Fig. 34). More simply these ratios indicate whether there was an increase or decrease in the number (or mass) of particles in each size range as a consequence of steam condensation. If the ratio is unity for a particle volume range there was no change in the number (and mass) of particles in that range; if the ratio is less than unity there was a decrease in number (and mass) of particles in that range; if the ratio is greater than unity there was an increase in the number (and mass) of particles in that size range.

Figures 35-85 give families of plots of these distribution function ratios vs particle volume. Each curve represents a different steam condensation rate. There are generally four plots of each particle size and substance; one for each concentration tested; the inlet concentration

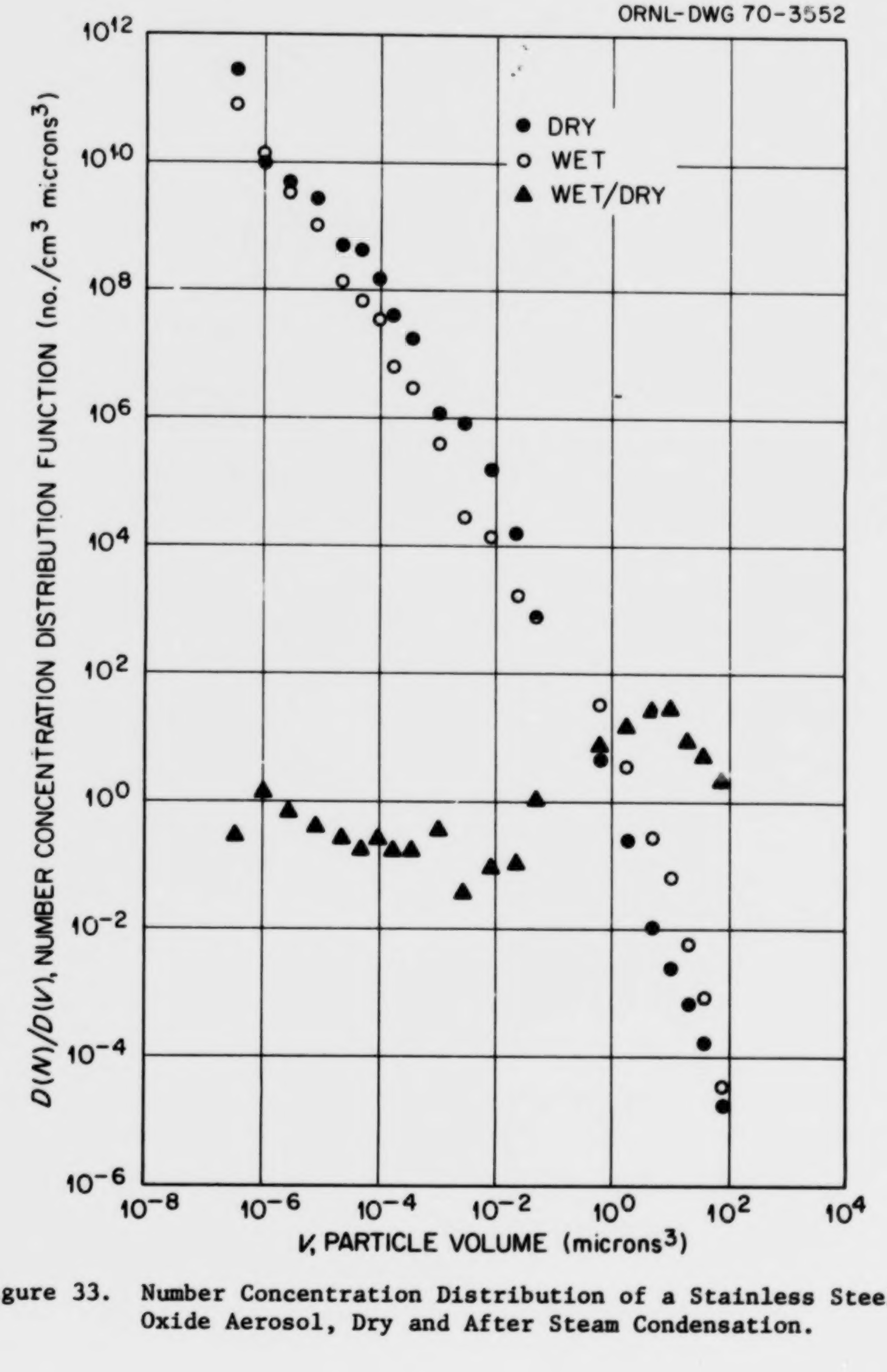

Figure 33. Number Concentration Distribution of a Stainless Steel Oxide Aerosol, Dry and After Steam Condensation.

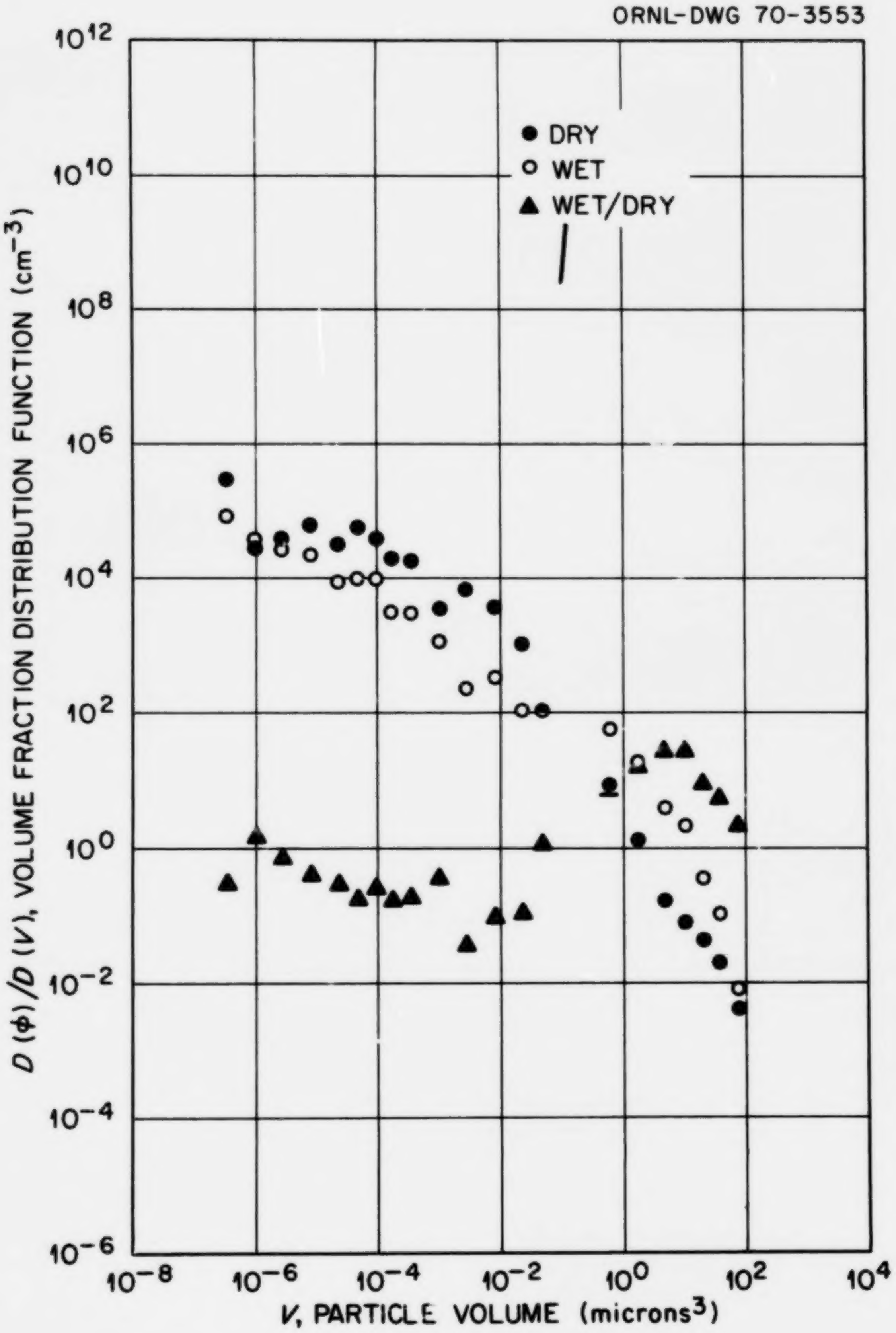

Figure 34. Volume Fraction Distribution of a Stainless Steel Oxide Aerosol, Dry and After Steam Condensation.

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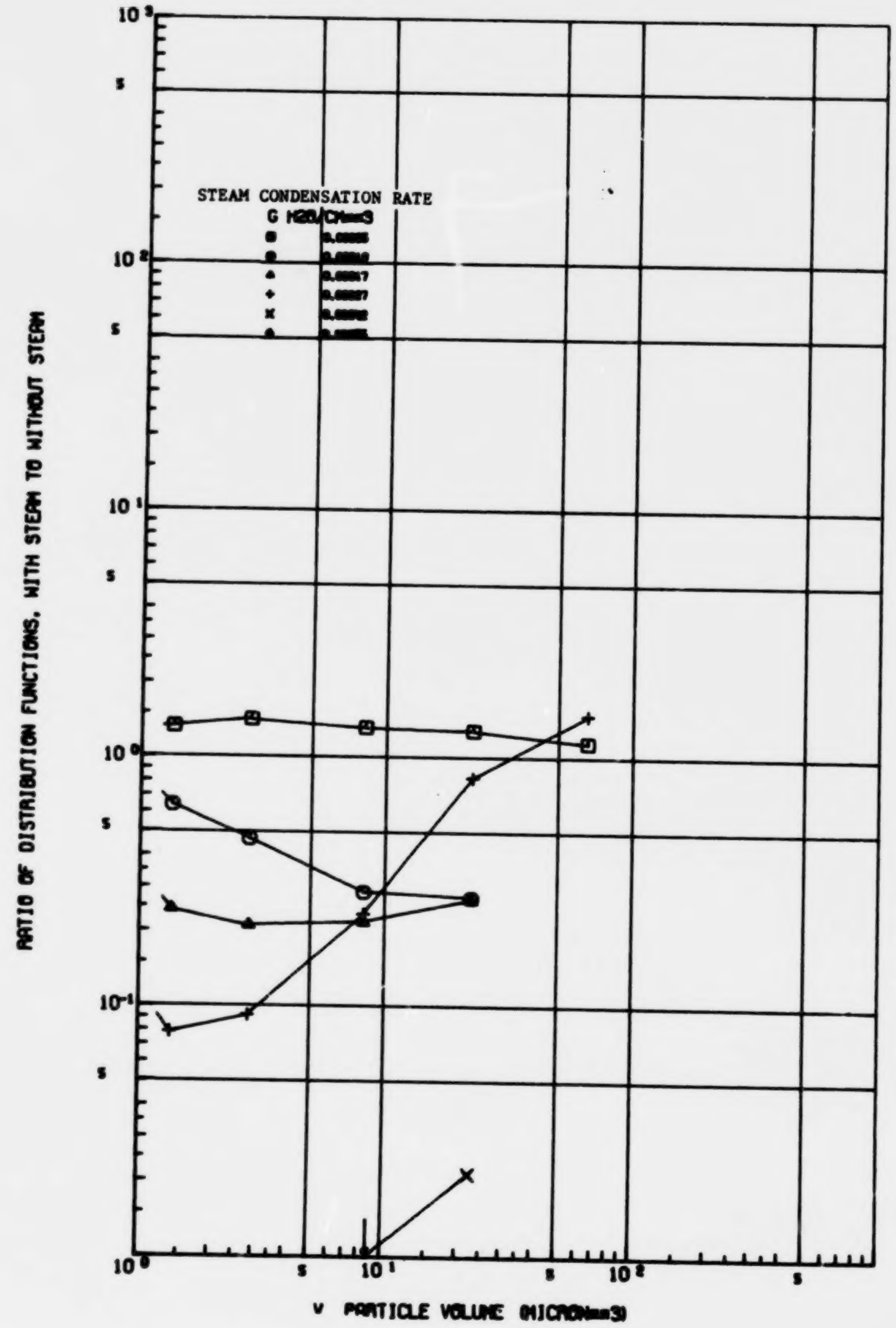


Figure 35. Latex, 1.9 Micron Mass Median Diameter, 0.9 x 10^3 particles/cm^3.

ORNL-DWG 70-8792

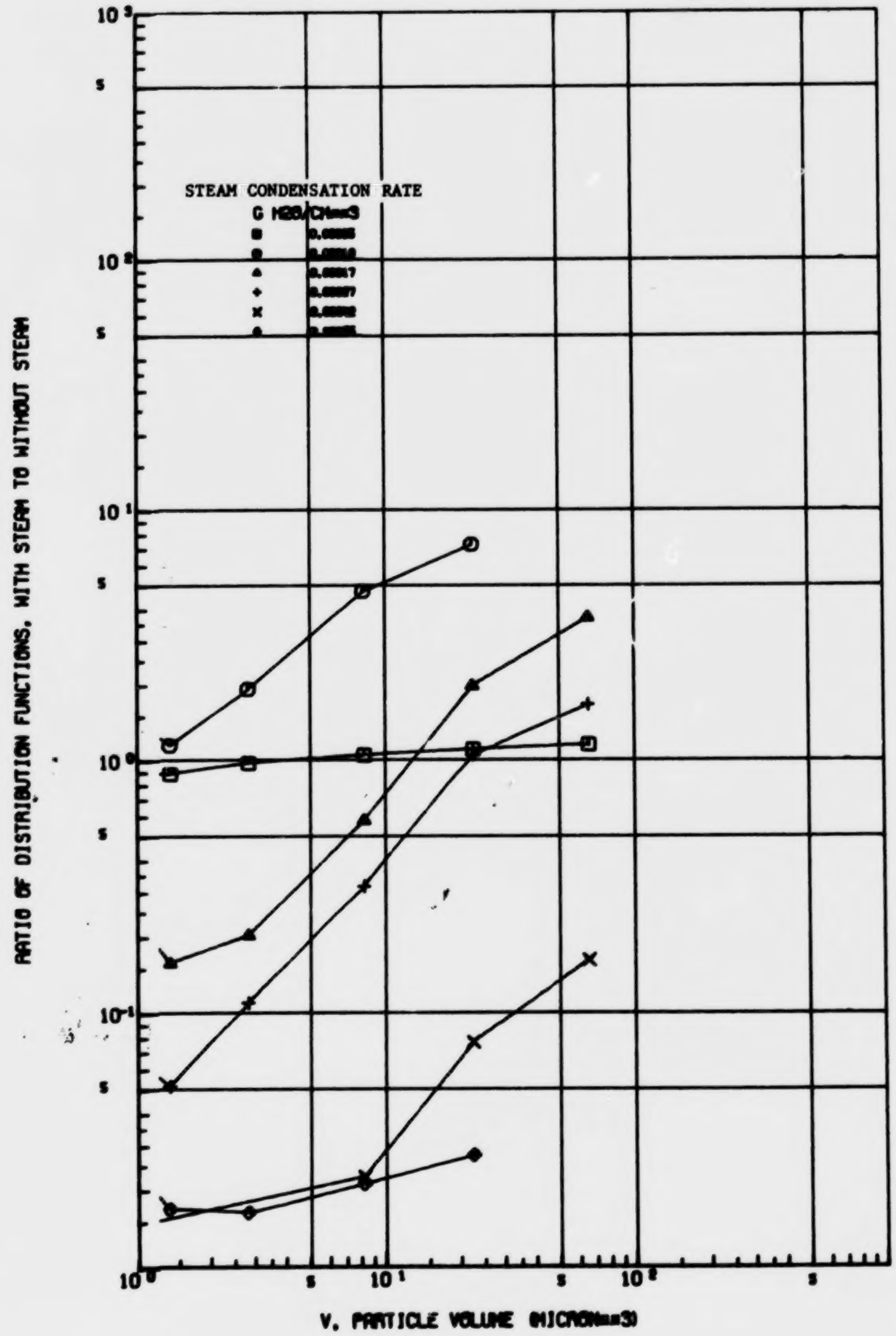


Figure 36. Latex, 1.9 Micron Mass Median Diameter, 1.8 x 10^3 particles/cm^3.

ORNL-DWG 70-8793

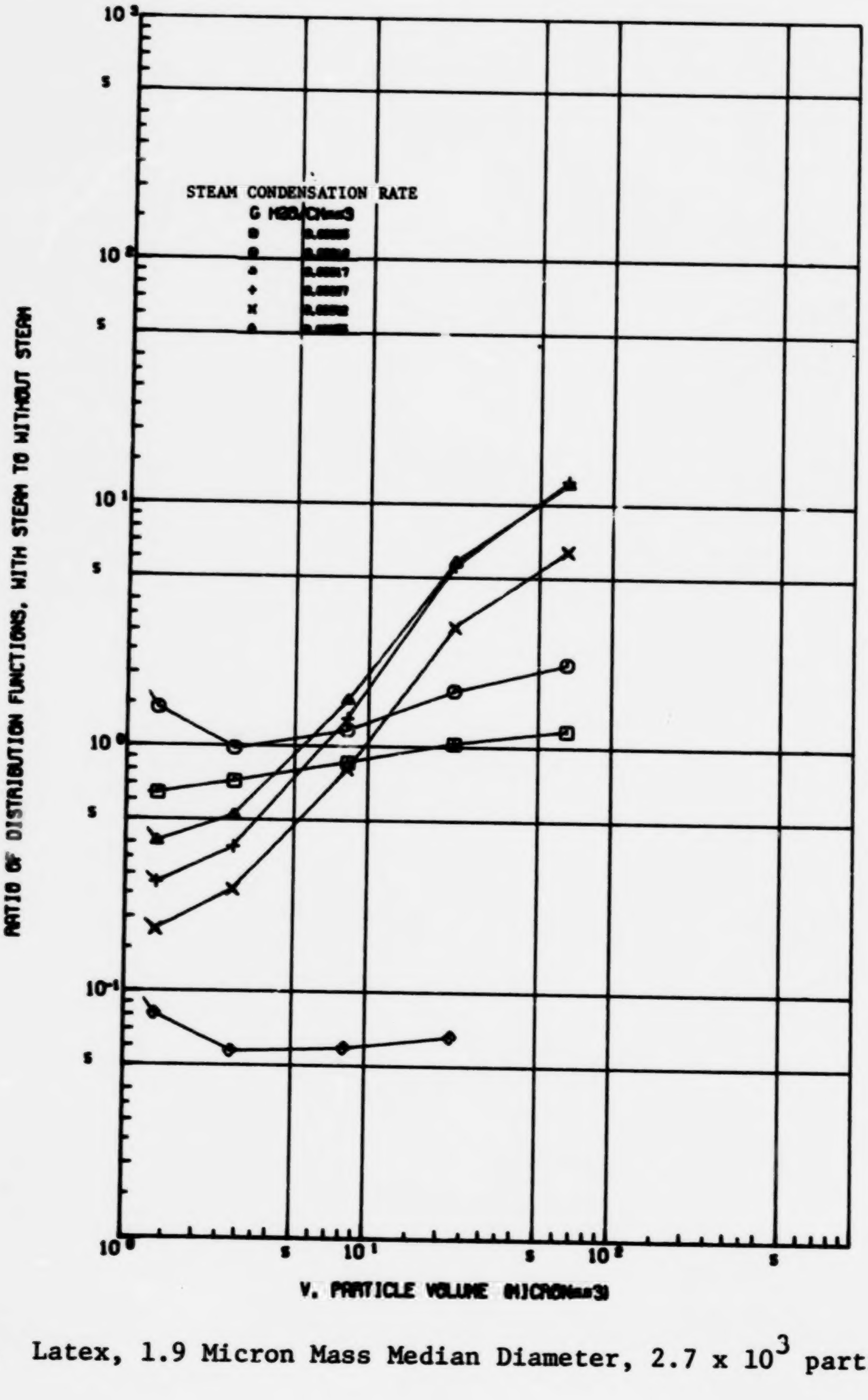


Figure 37. Latex, 1.9 Micron Mass Median Diameter, 2.7 x 10^3 particles/cm^3.

ORNL-DWG 70-8794

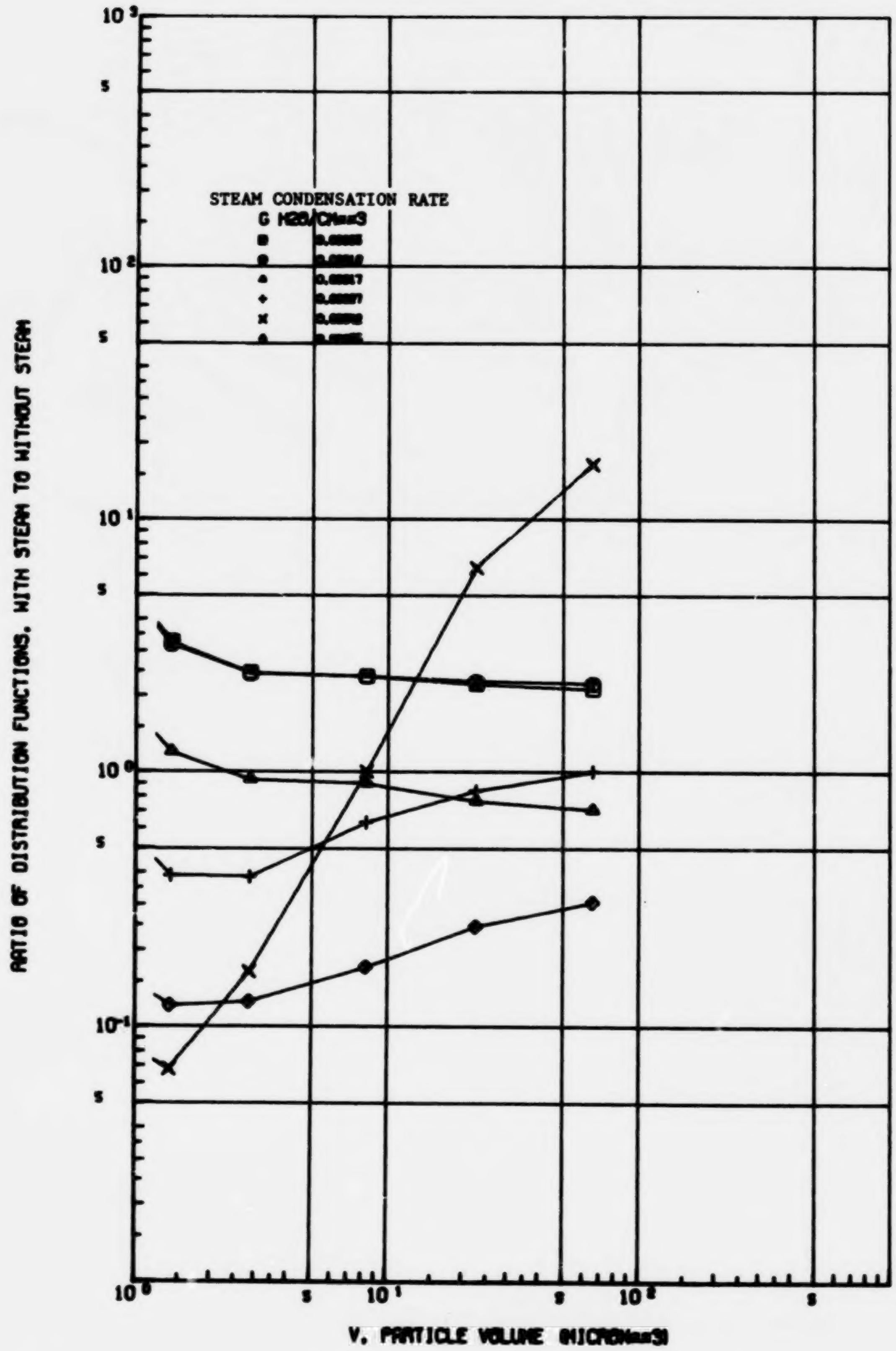


Figure 38. Latex, 1.9 Micron Mass Median Diameter, 3.5 x 10^3 particles/cm^3.

ORNL-DWG 70-8783

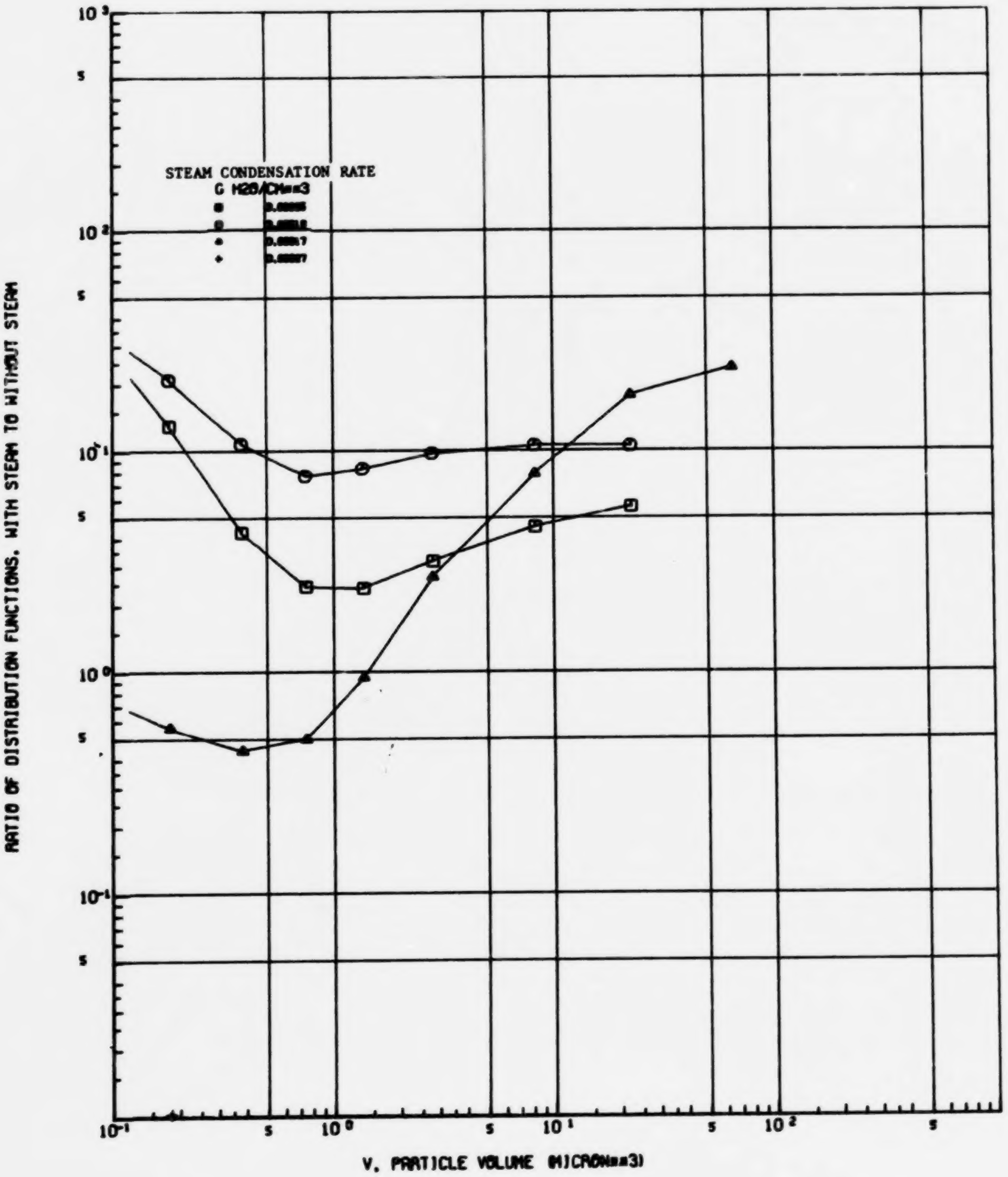


Figure 39. Latex, 1.1 Micron Mass Median Diameter, 1.0 x 10^2 particles/cm^3

ORNL-DWG 70-8784

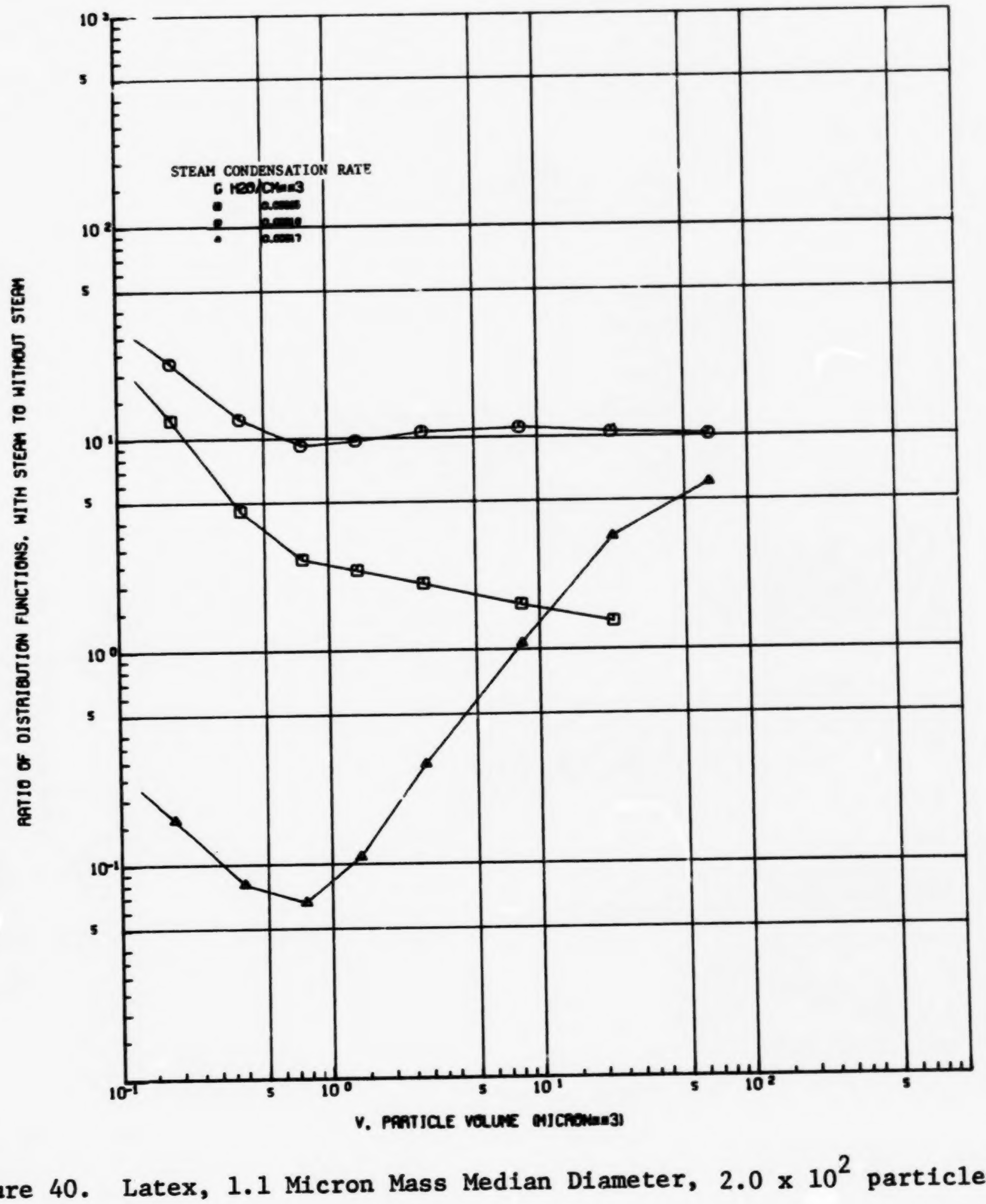


Figure 40. Latex, 1.1 Micron Mass Median Diameter, 2.0 x 10^2 particles/cm^3

ORNL-DWG 70-8785

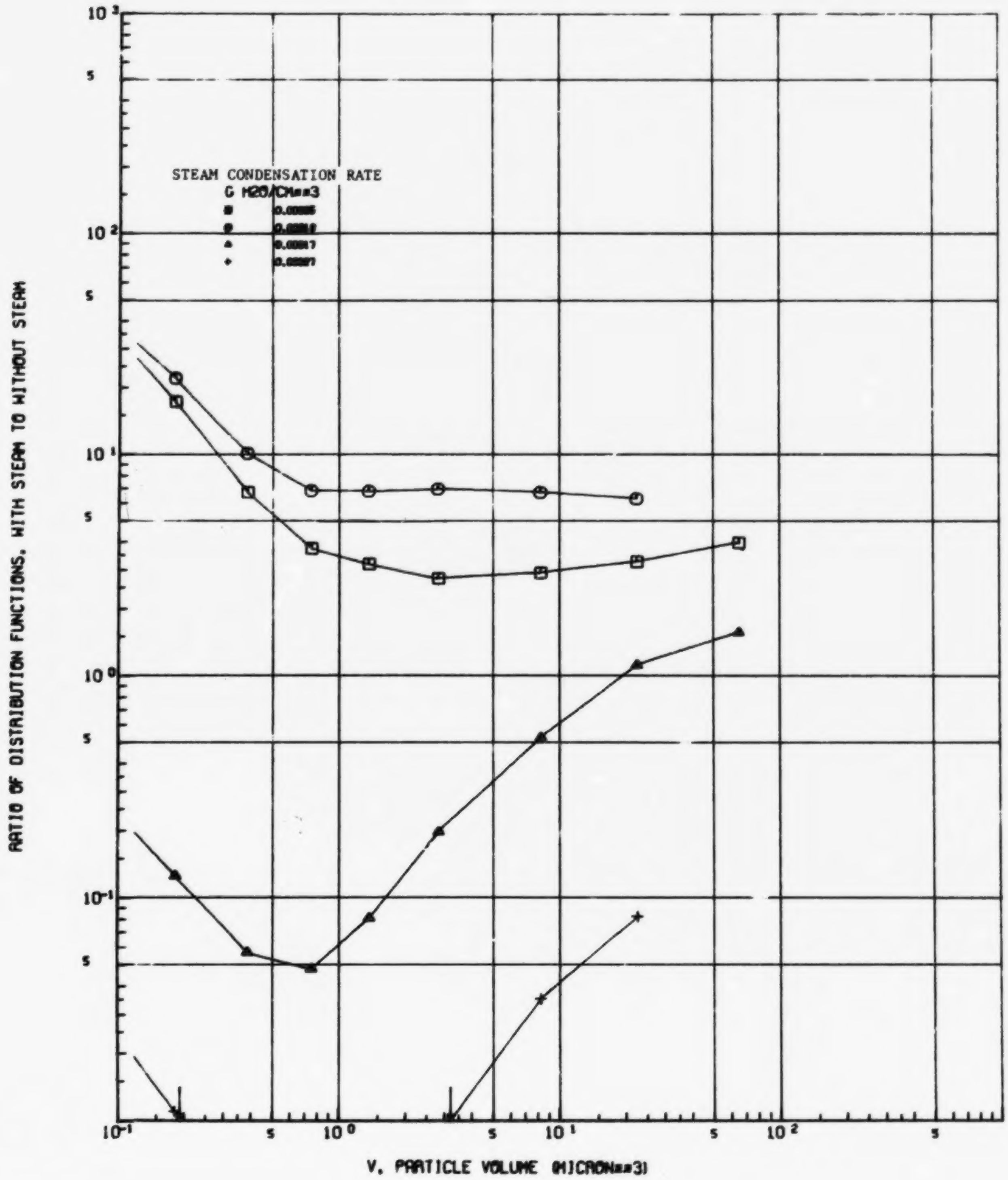


Figure 41. Latex, 1.1 Micron Mass Median Diameter, 3.0 x 10^2 particles/cm^3

ORNL-DWG 70-8786

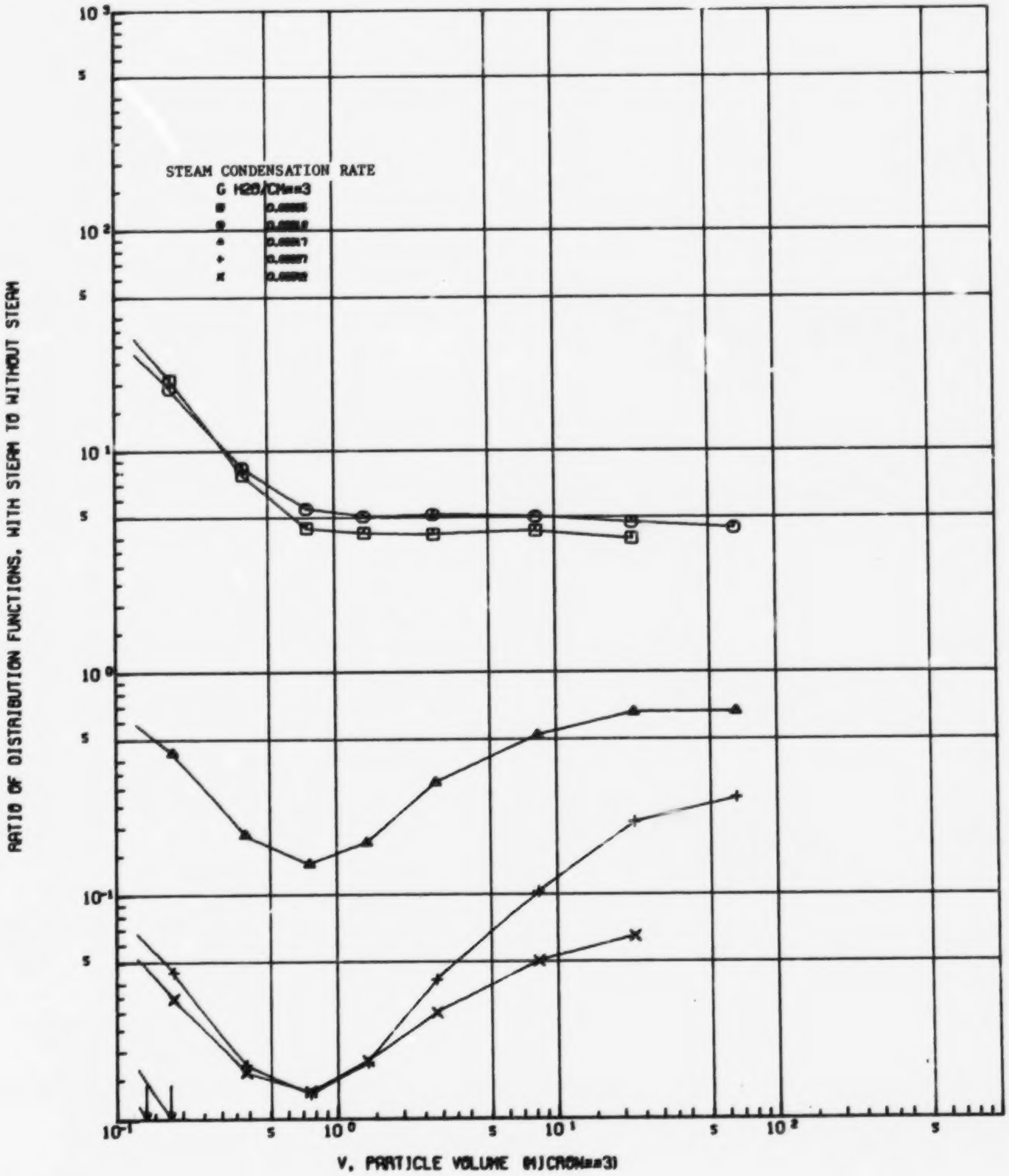


Figure 42. Latex, 1.1 Micron Mass Median Diameter, 4.0 x 10^2 particles/cm^3

ORNL-DWG 70-8787

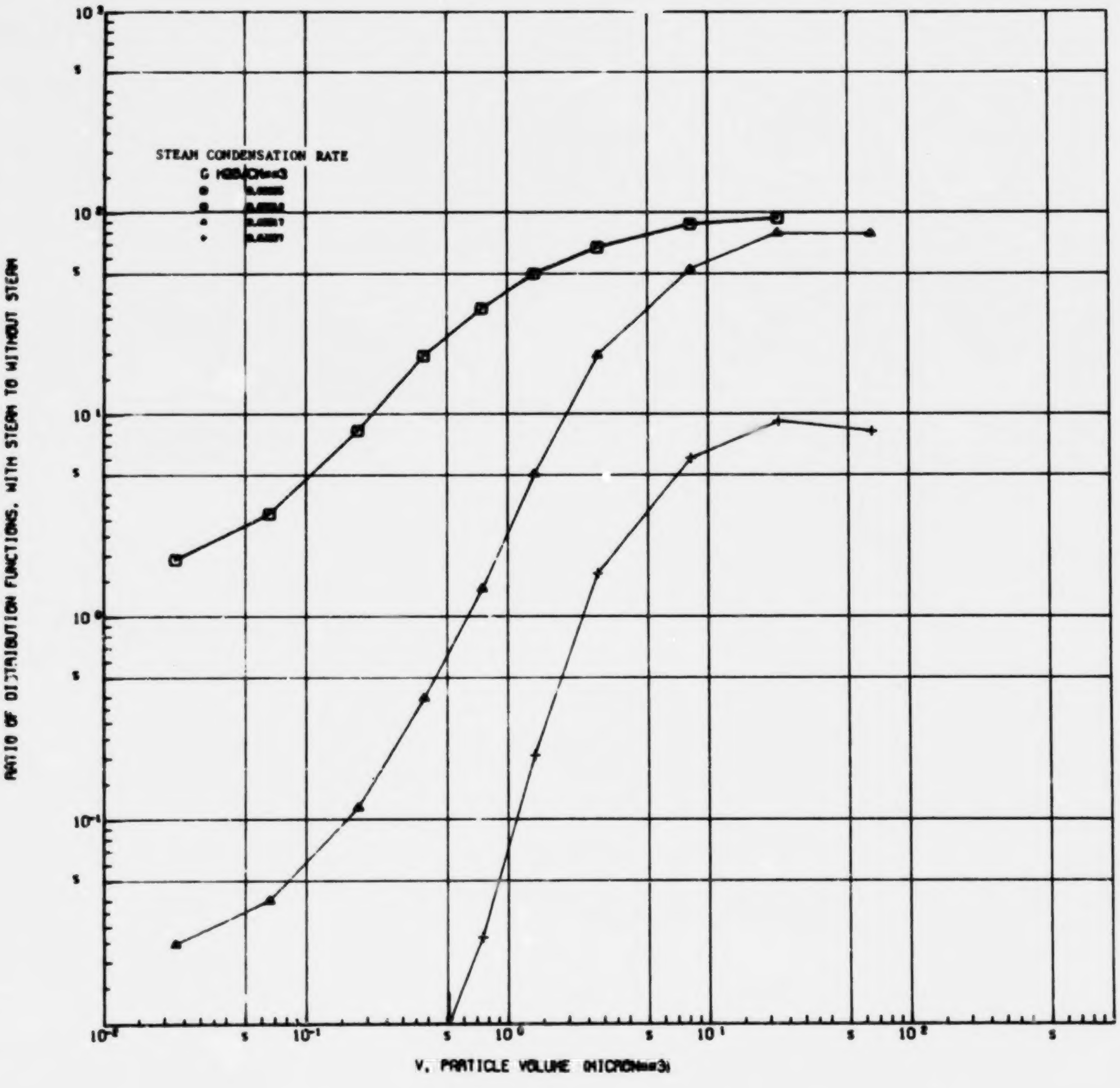


Figure 43. Latex, 0.5 Micron Mass Median Diameter, 1.0 x 10^2 particles/cm^3

ORNL-DWG 70-8788

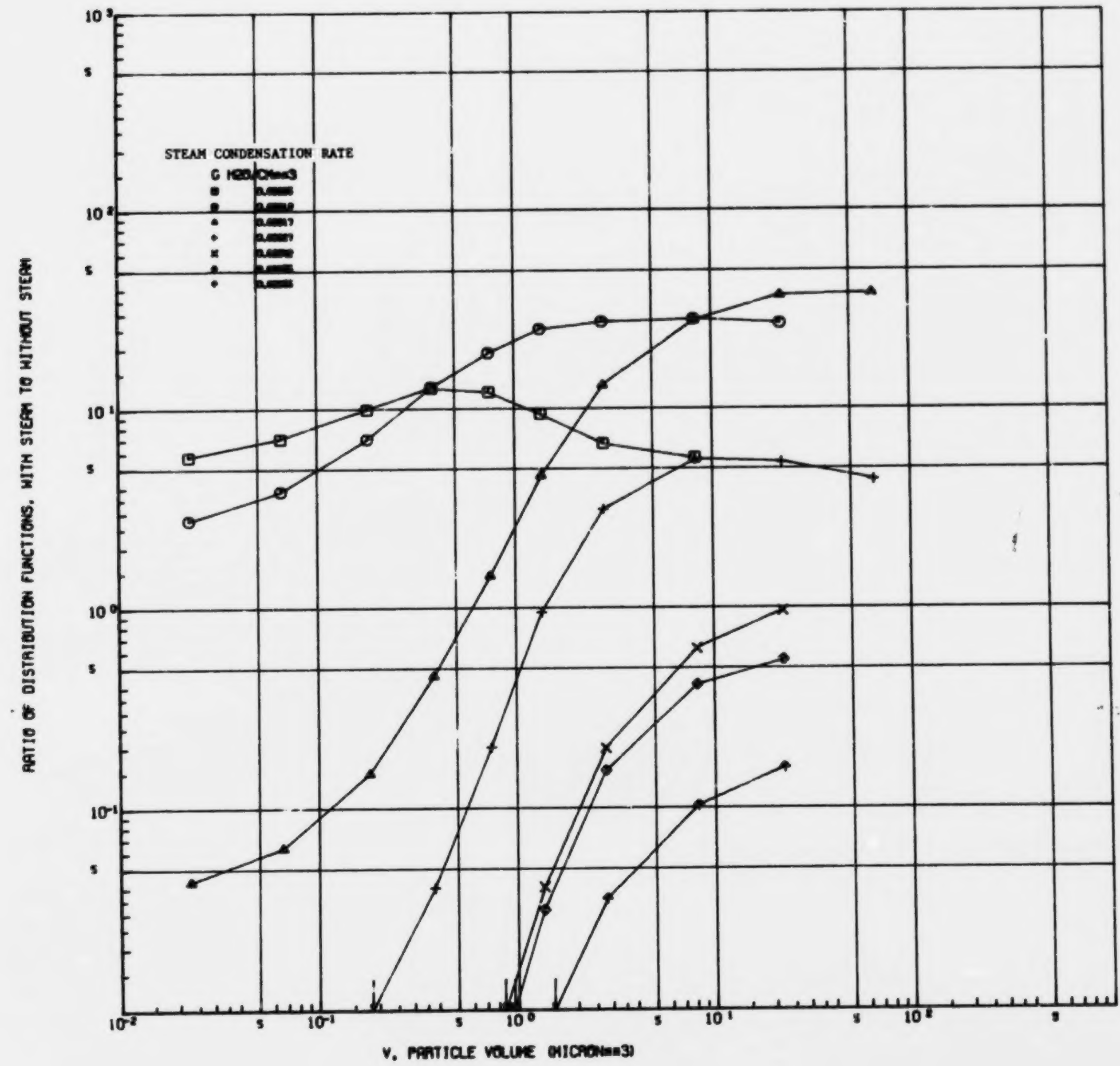


Figure 44. Latex, 0.5 Micron Mass Median Diameter, 2.0 x 10^2 particles/cm^3

ORNL-DWG 70-8789

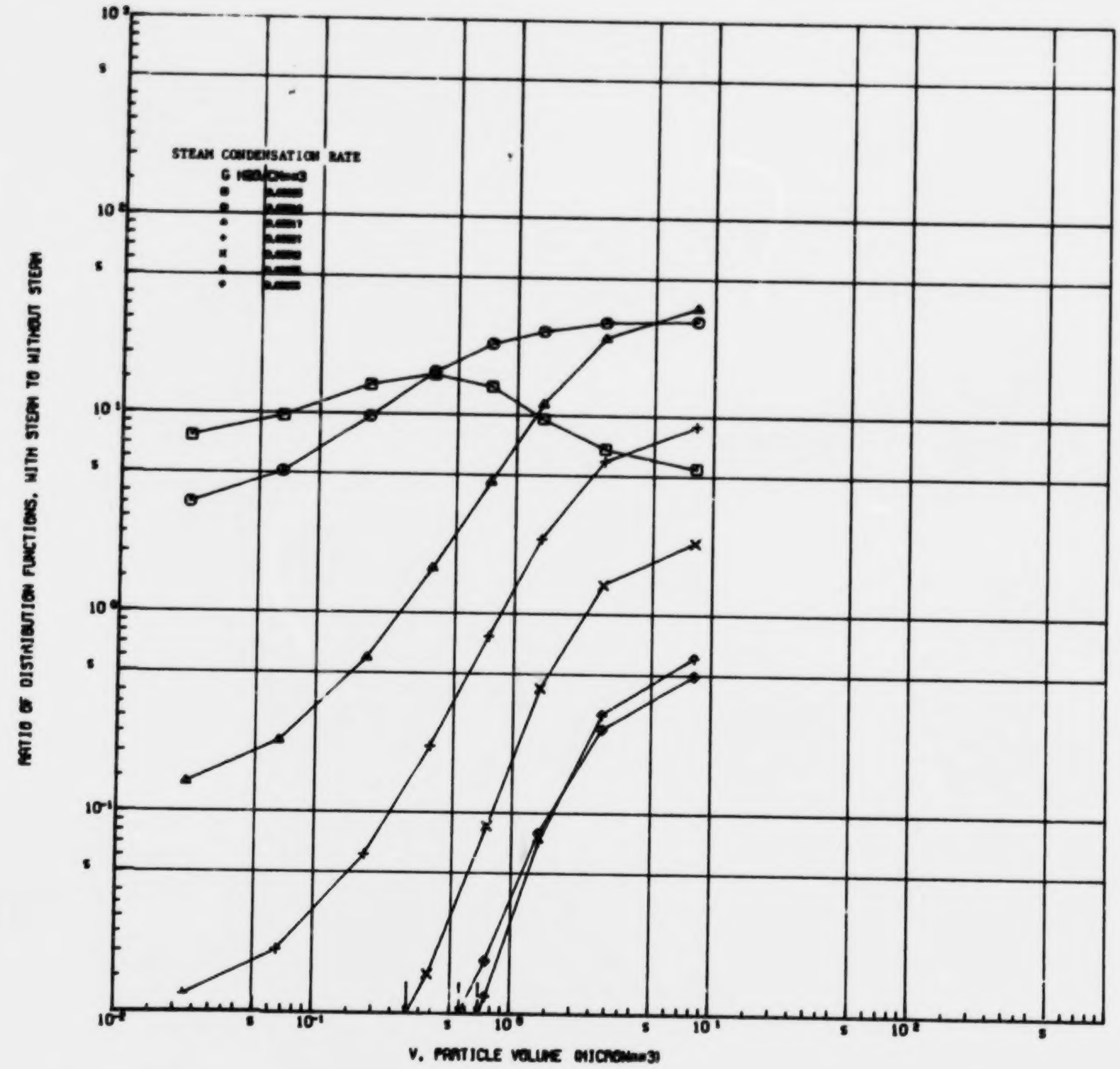


Figure 45. Latex, 0.5 Micron Mass Median Diameter, 3.0 x 10^2 particles/cm^3

ORNL-DWG 70-8790

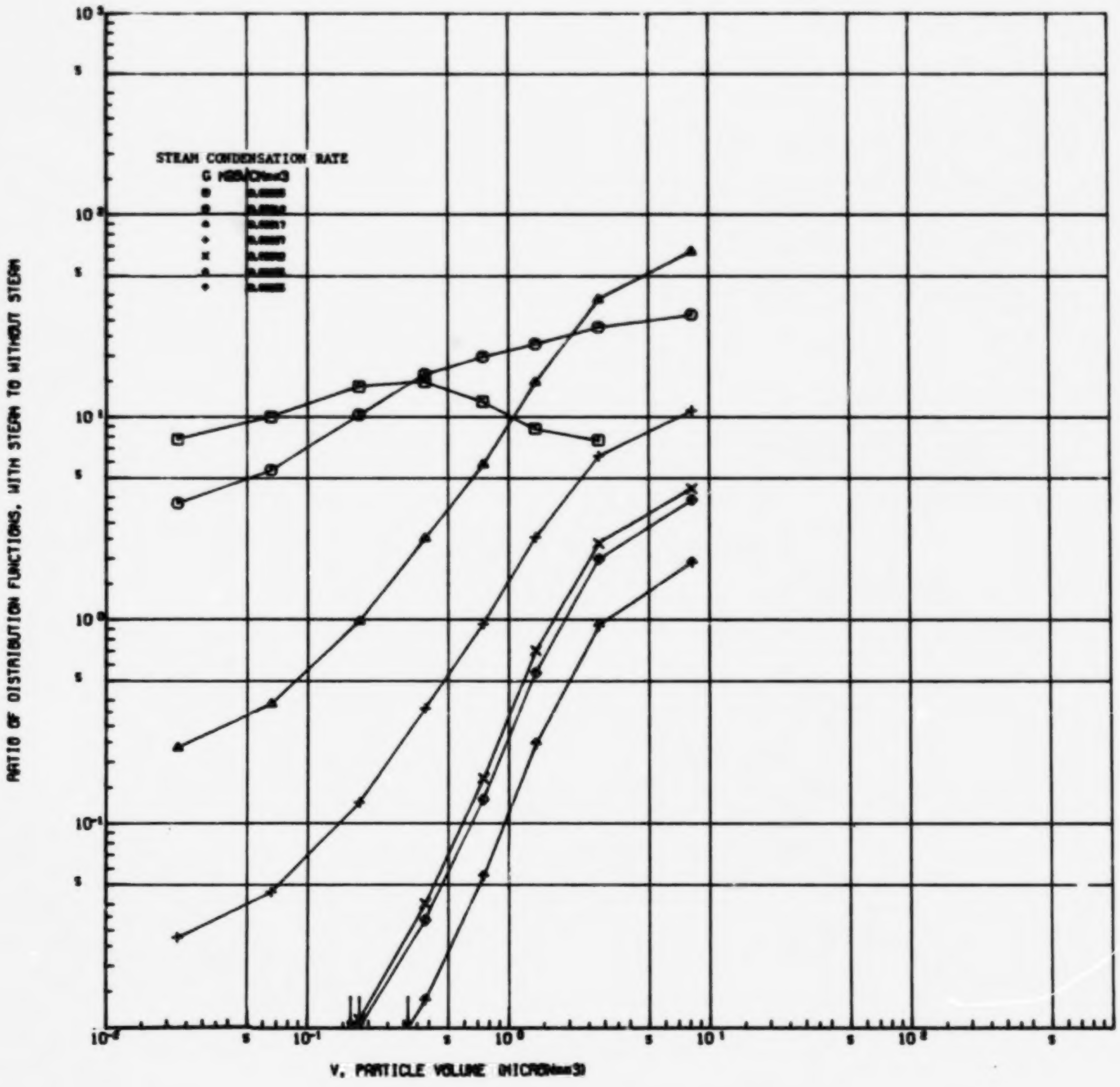


Figure 46. Latex, 0.5 Micron Mass Median Diameter, 4.0 x 10^2 particles/cm^3

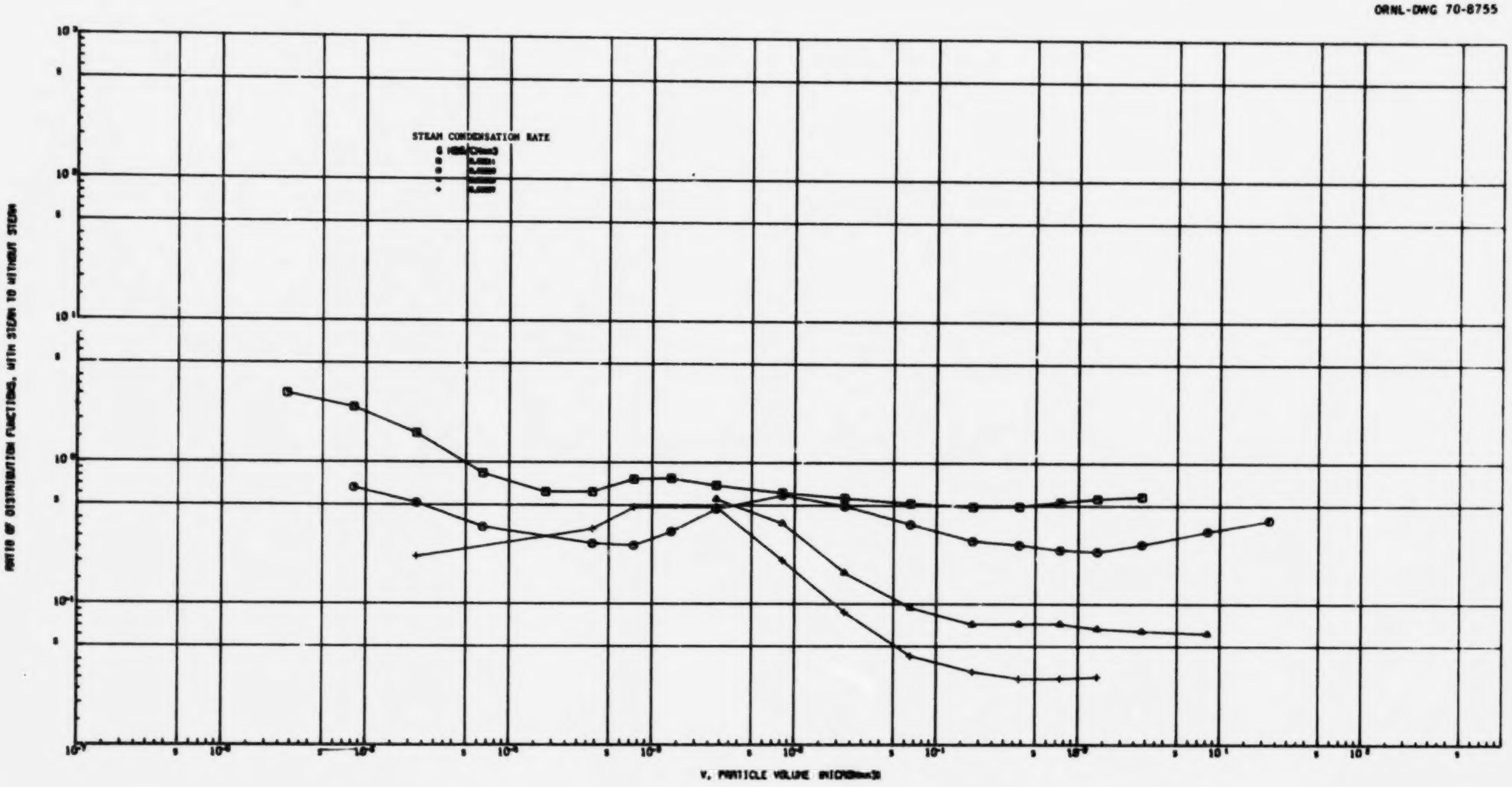


Figure 47. Dioctylphthalate, 0.5 Micron Mass Median Diameter, 1.0 x 10^4 particles/cm^3

ORNL-DWG 70-8756

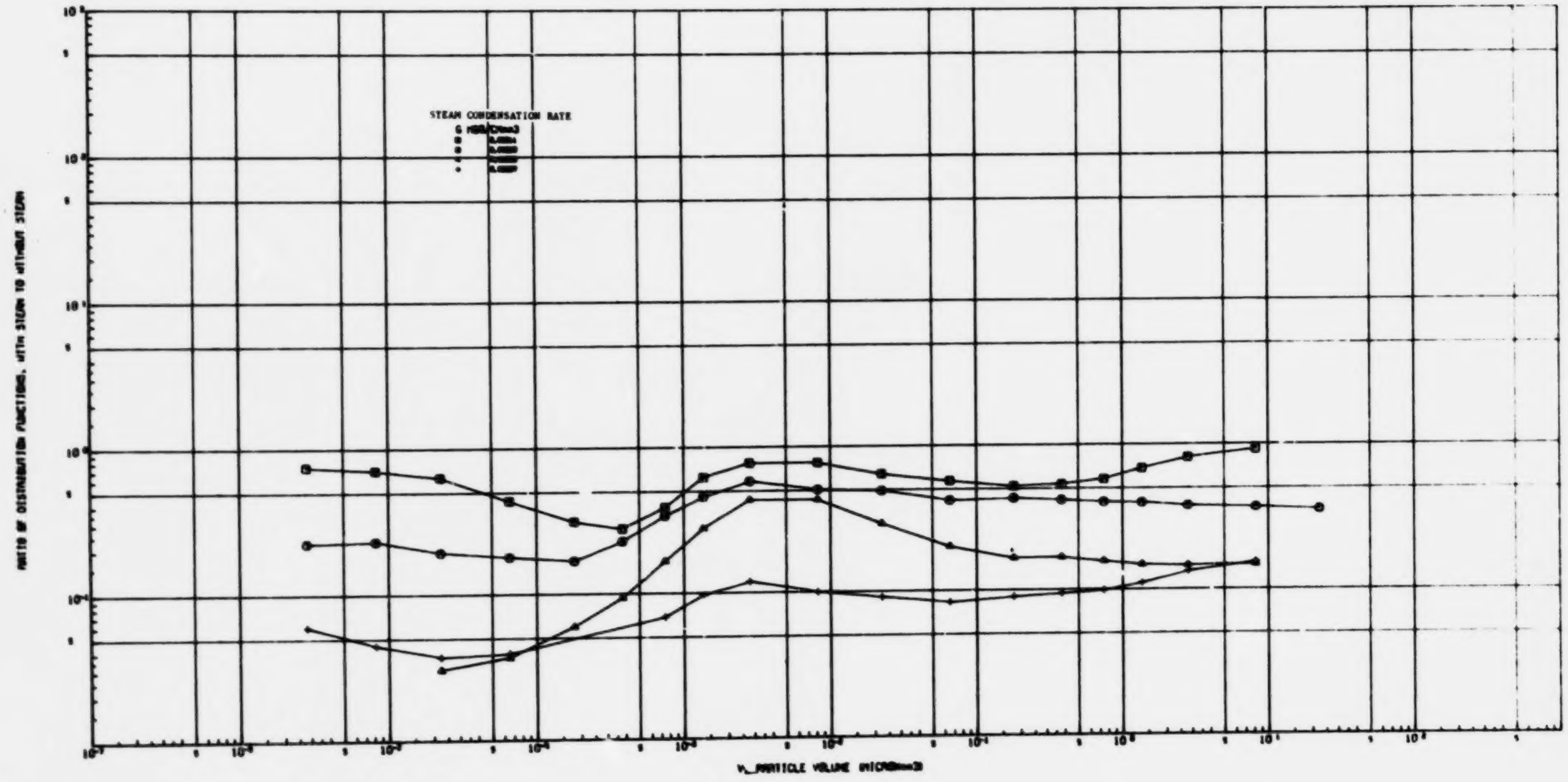


Figure 48. Dioctylphthalate, 0.5 Micron Mass Median Diameter, 2.0 x 10^4 particles/cm^3

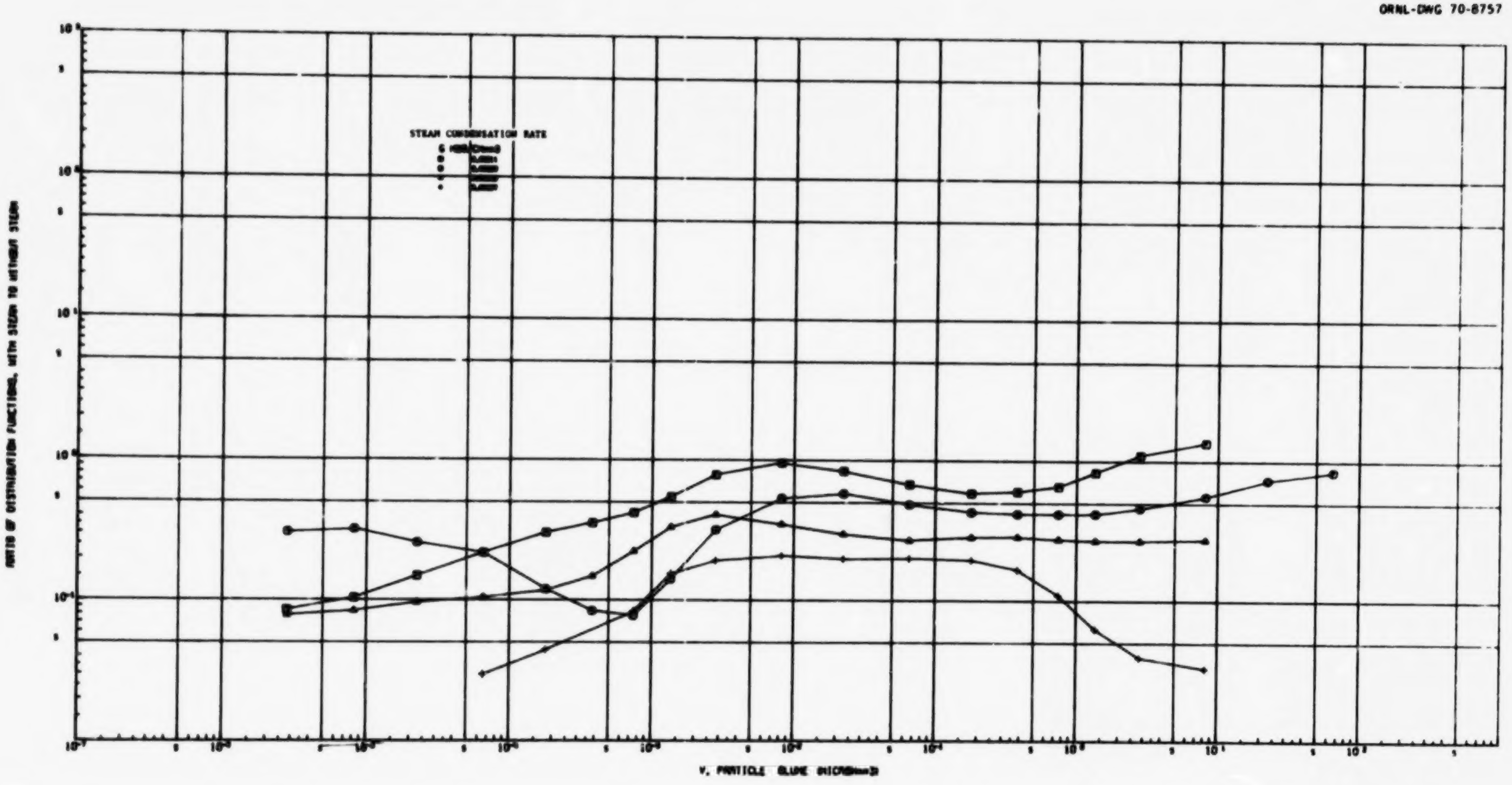


Figure 49. Dioctylphthalate, 0.5 Micron Mass Median Diameter, 3.0 x 10^4 particles/cm^3

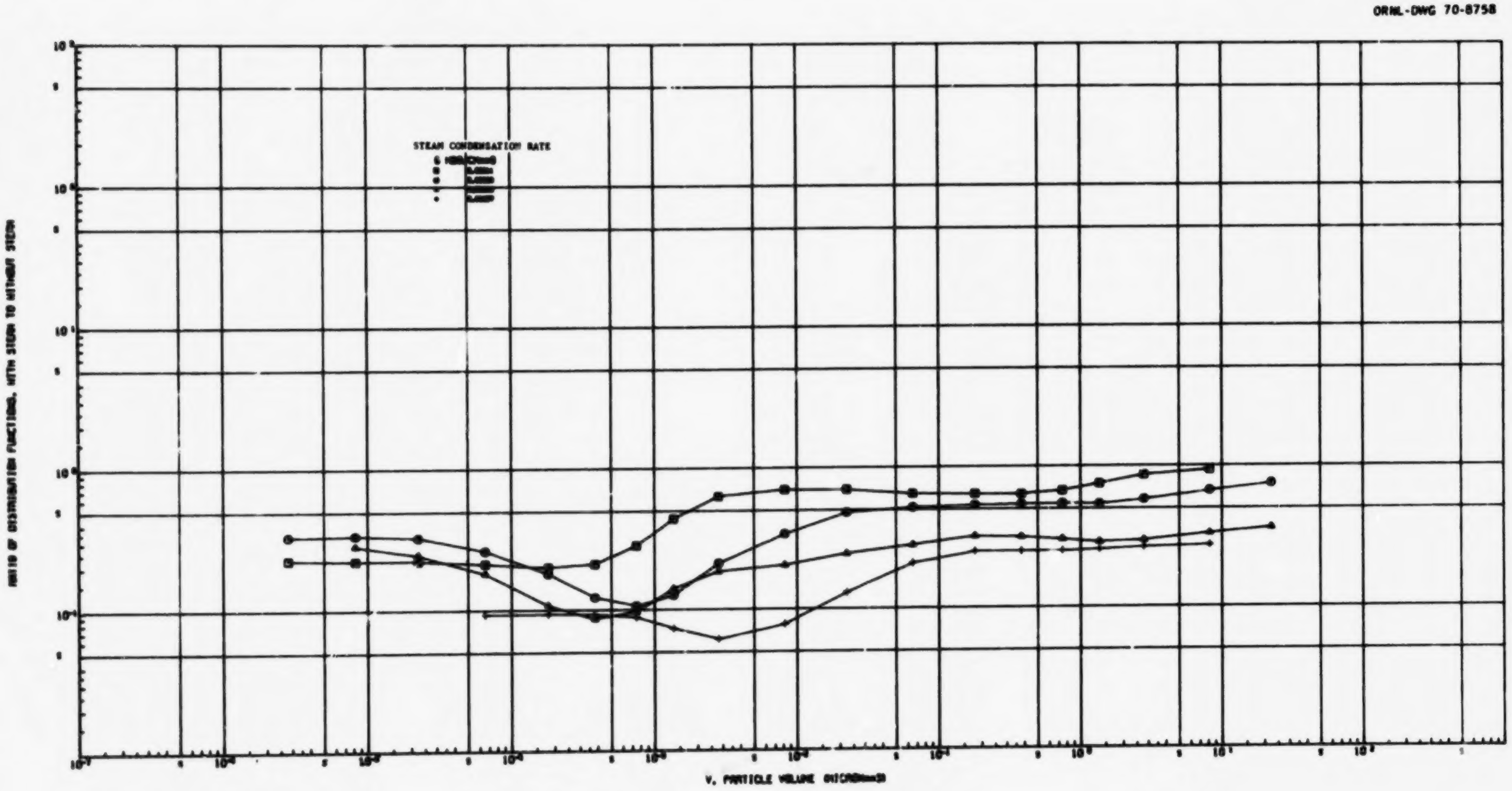


Figure 50. Dioctylphthalate, 0.5 Micron Mass Median Diameter, 4.0 x 10^4 particles/cm^3

ORNL-DWG 70-8751

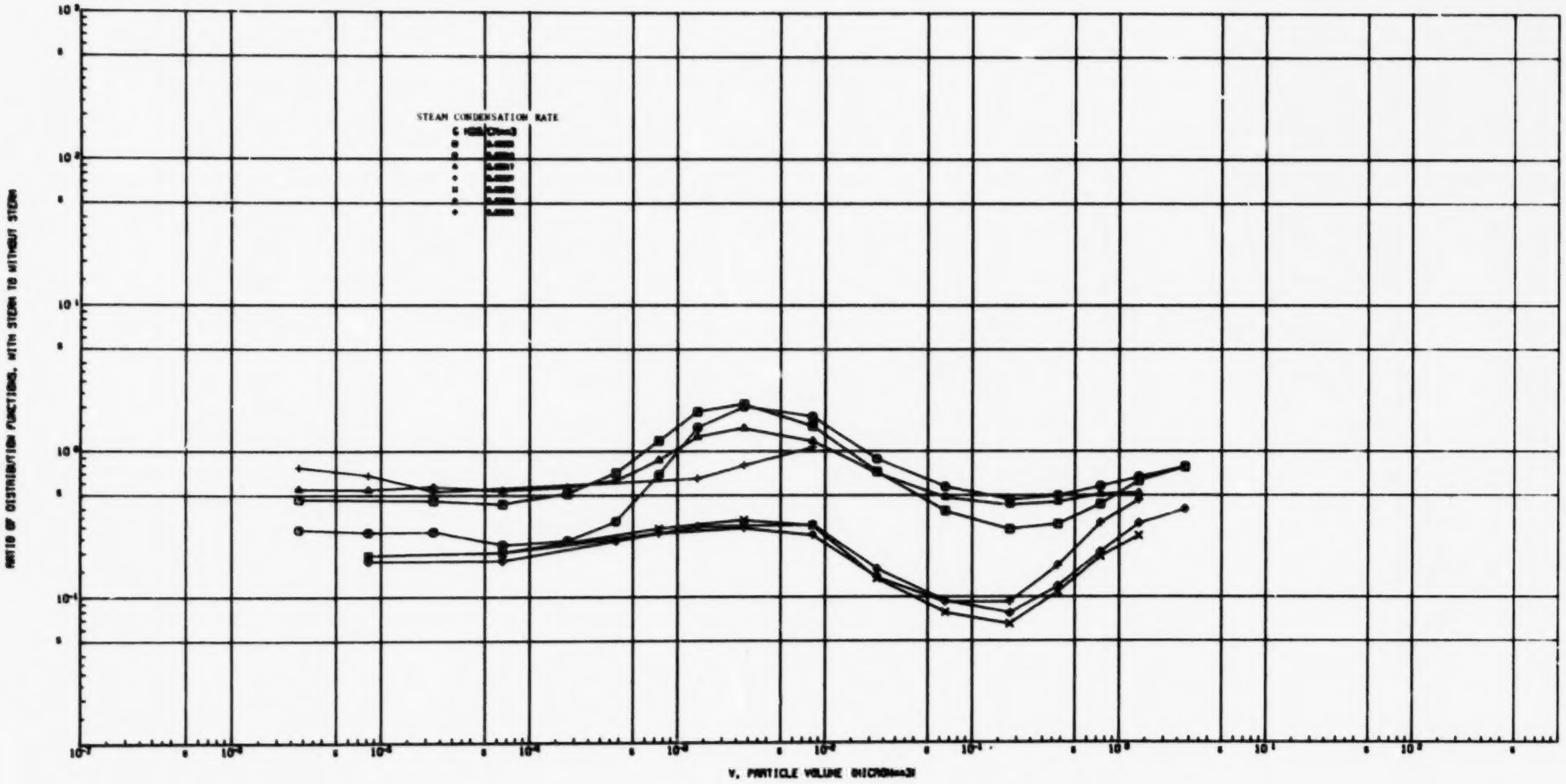


Figure 51. Dioctylphthalate, 0.2 Micron Mass Median Diameter, 1.0 x 10^4 particles/cm^3

ORNL-DWG 70-8752

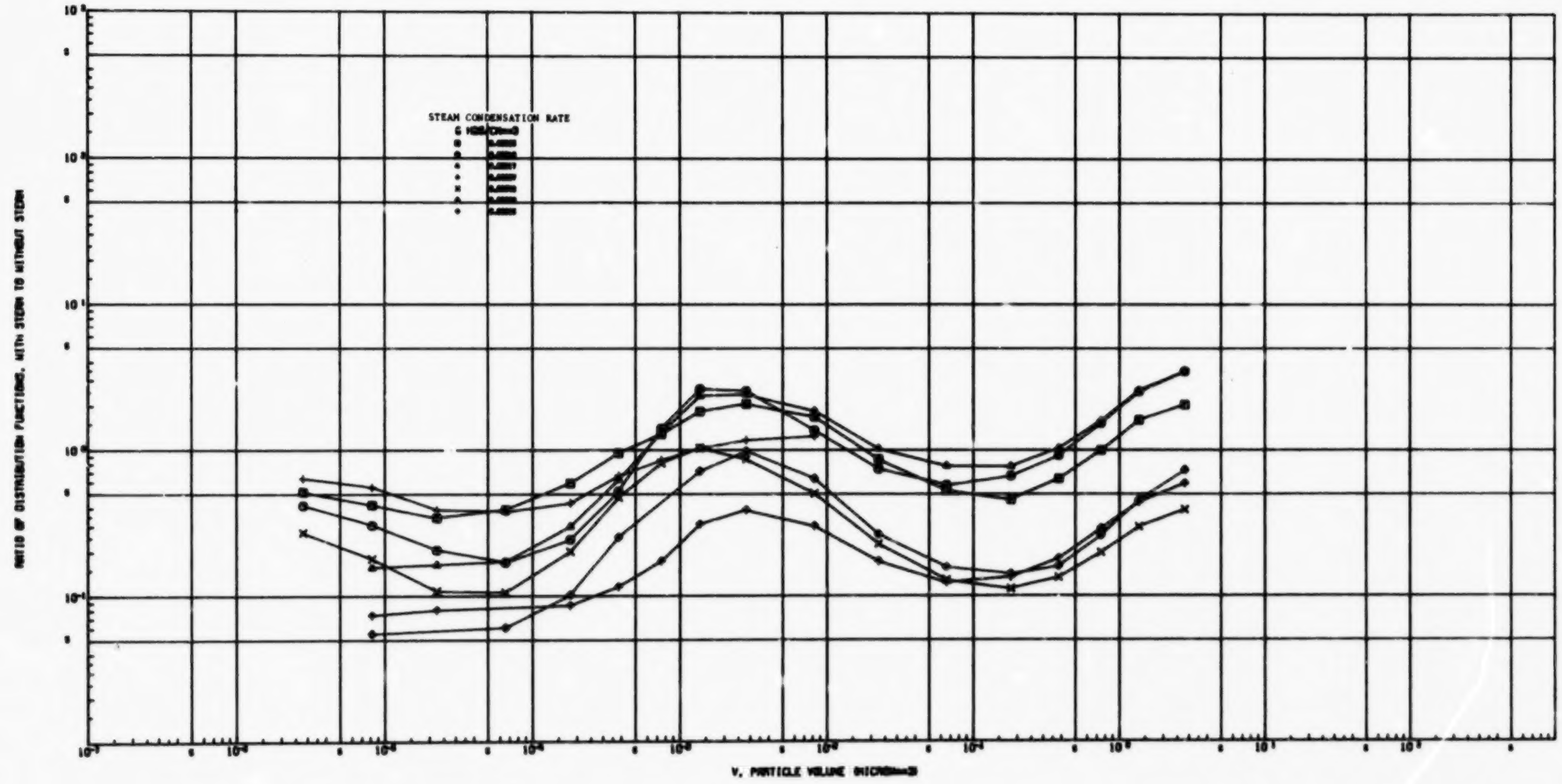


Figure 52. Dioctylphthalate, 0.2 Micron Mass Median Diameter, 2.0 x 10^4 particles/cm^3

ORNL-DWG 70-8753

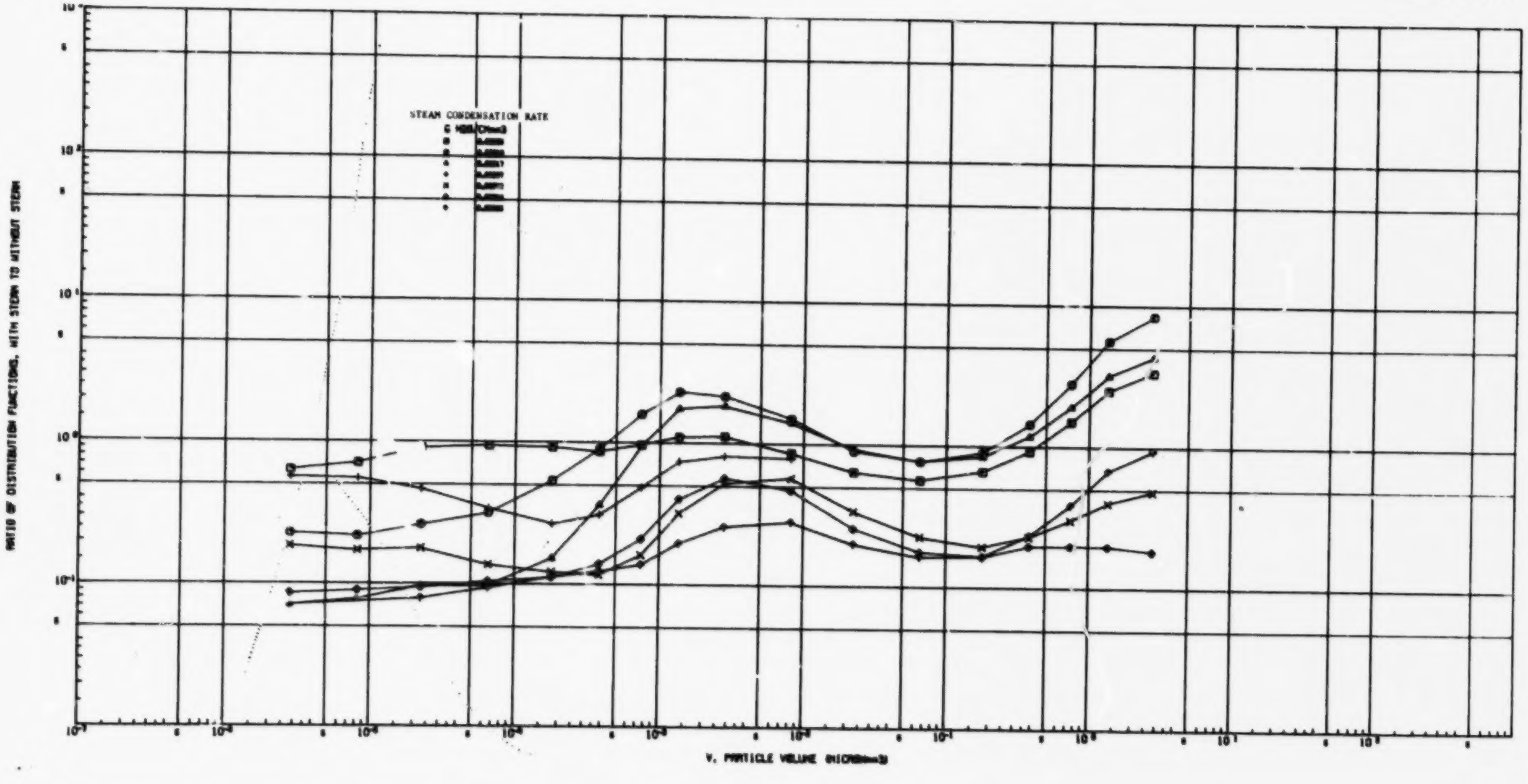


Figure 53. Dioctylphthalate, 0.2 Micron Mass Median Diameter, 3.0 x 10^4 particles/cm^3

ORNL-DWG 70-8754

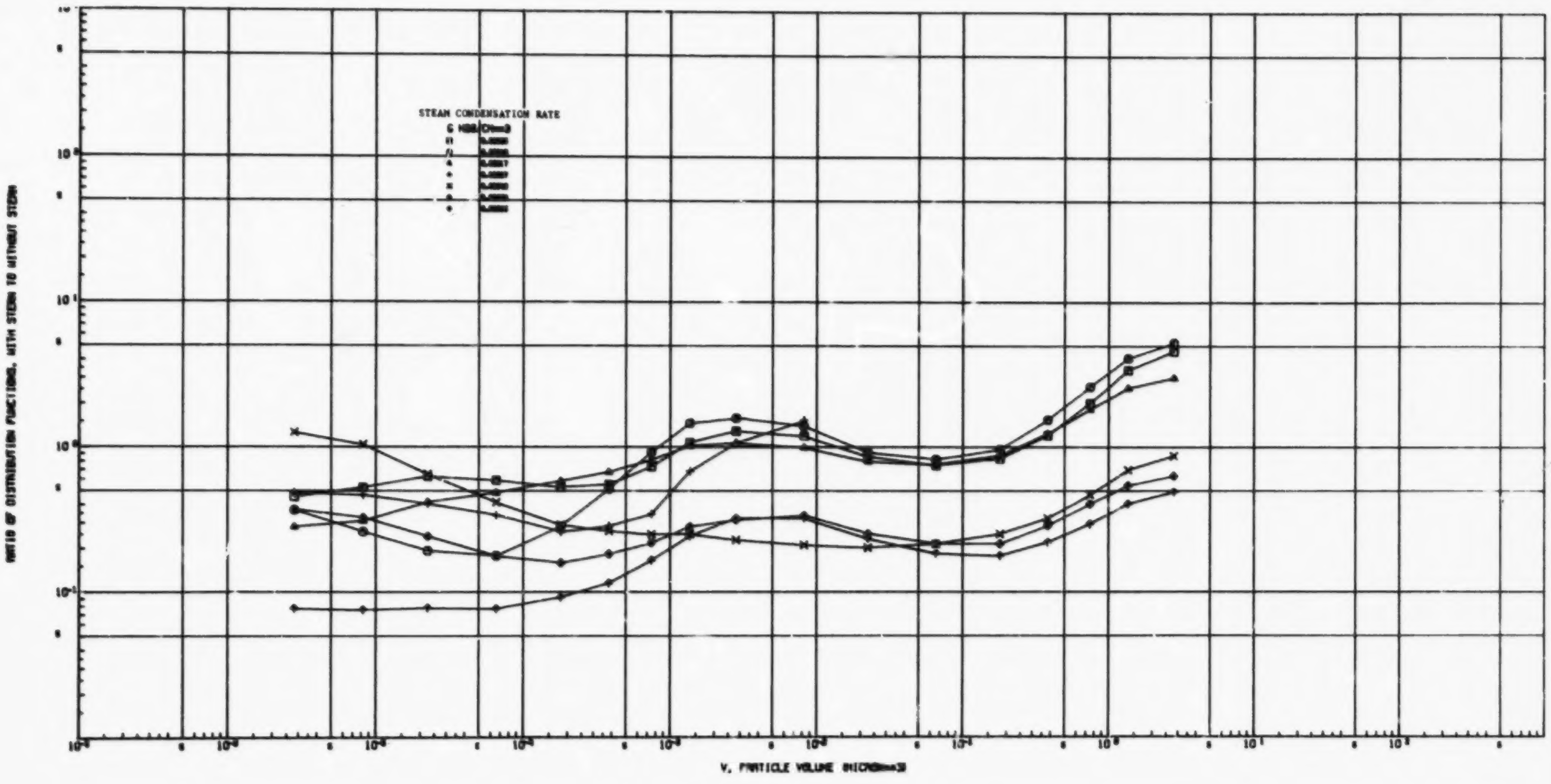


Figure 54. Dioctylphthalate, 0.2 Micron Mass Median Diameter, 4.0 x 10^4 particles/cm^3

ORNL-DWG 70-8759

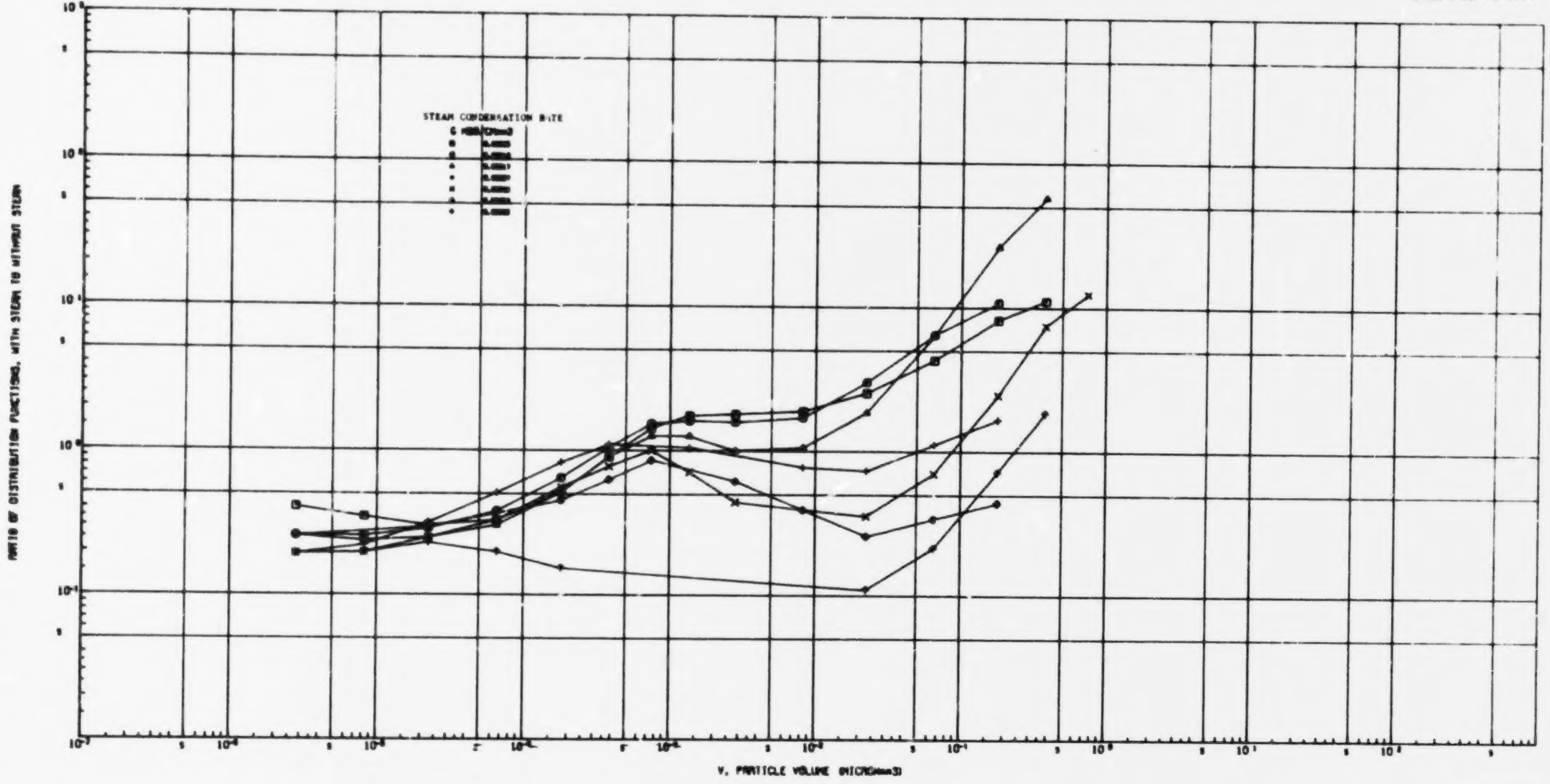


Figure 55. Dioctylphthalate, 0.1 Micron Mass Median Diameter, 1.9 x 10^4 particles/cm^3

ORNL-DWG 70-8760

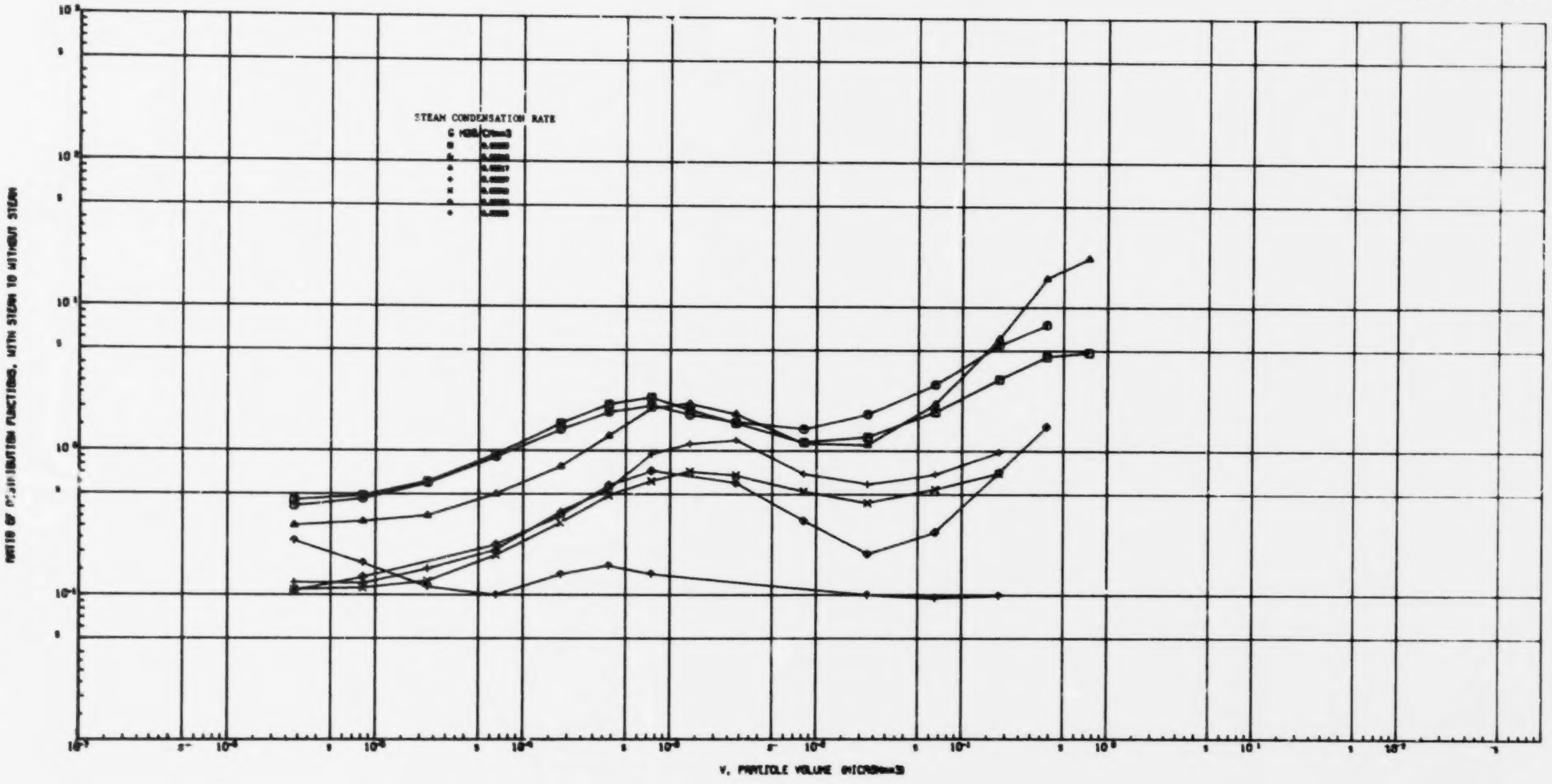


Figure 56. Dioctylphthalate, 0.1 Micron Mass Median Diameter, 3.8 x 10^4 particles/cm^3

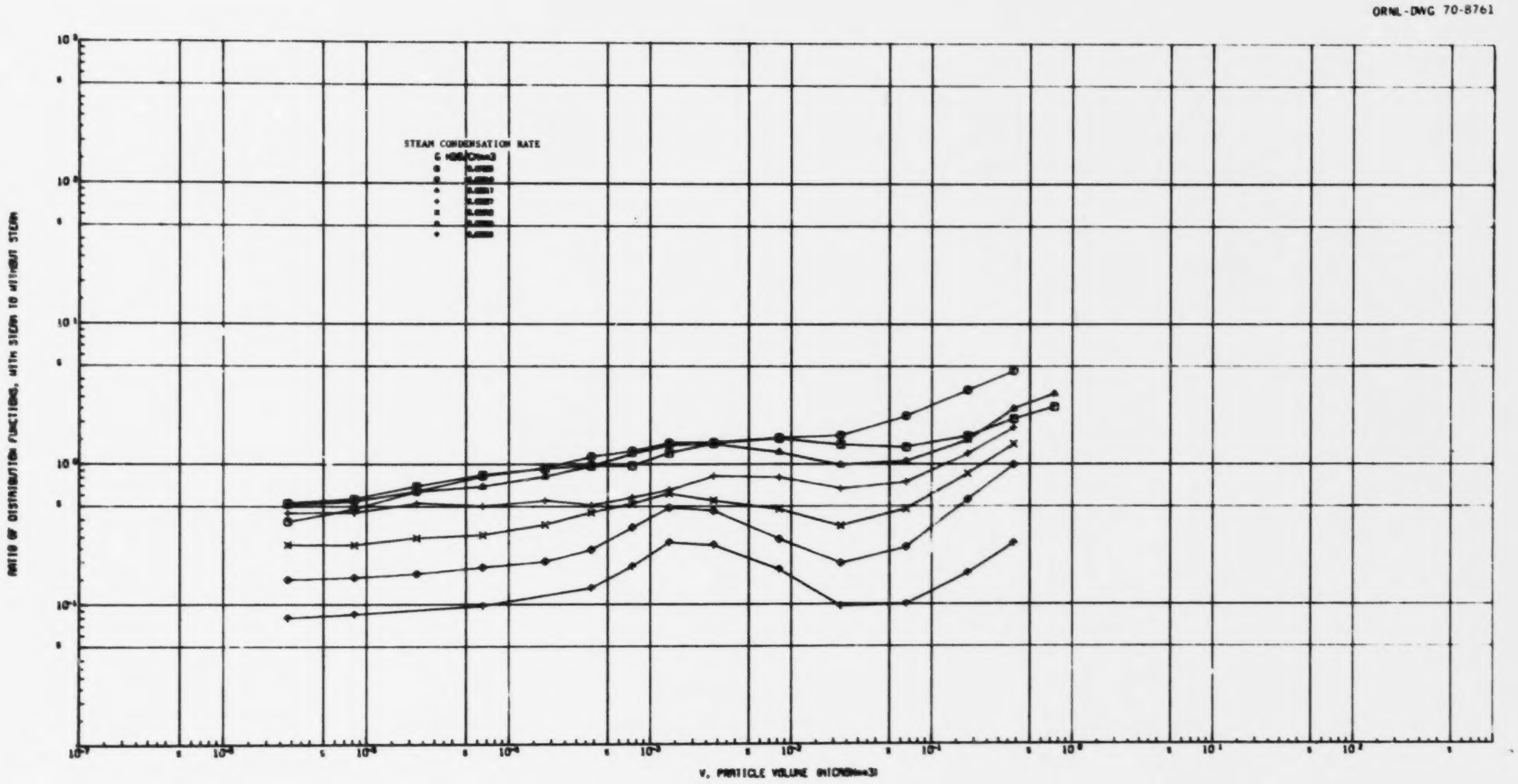


Figure 57. Dioctylphthalate, 0.1 Micron Mass Median Diameter, 5.7 x 10^4 particles/cm^3

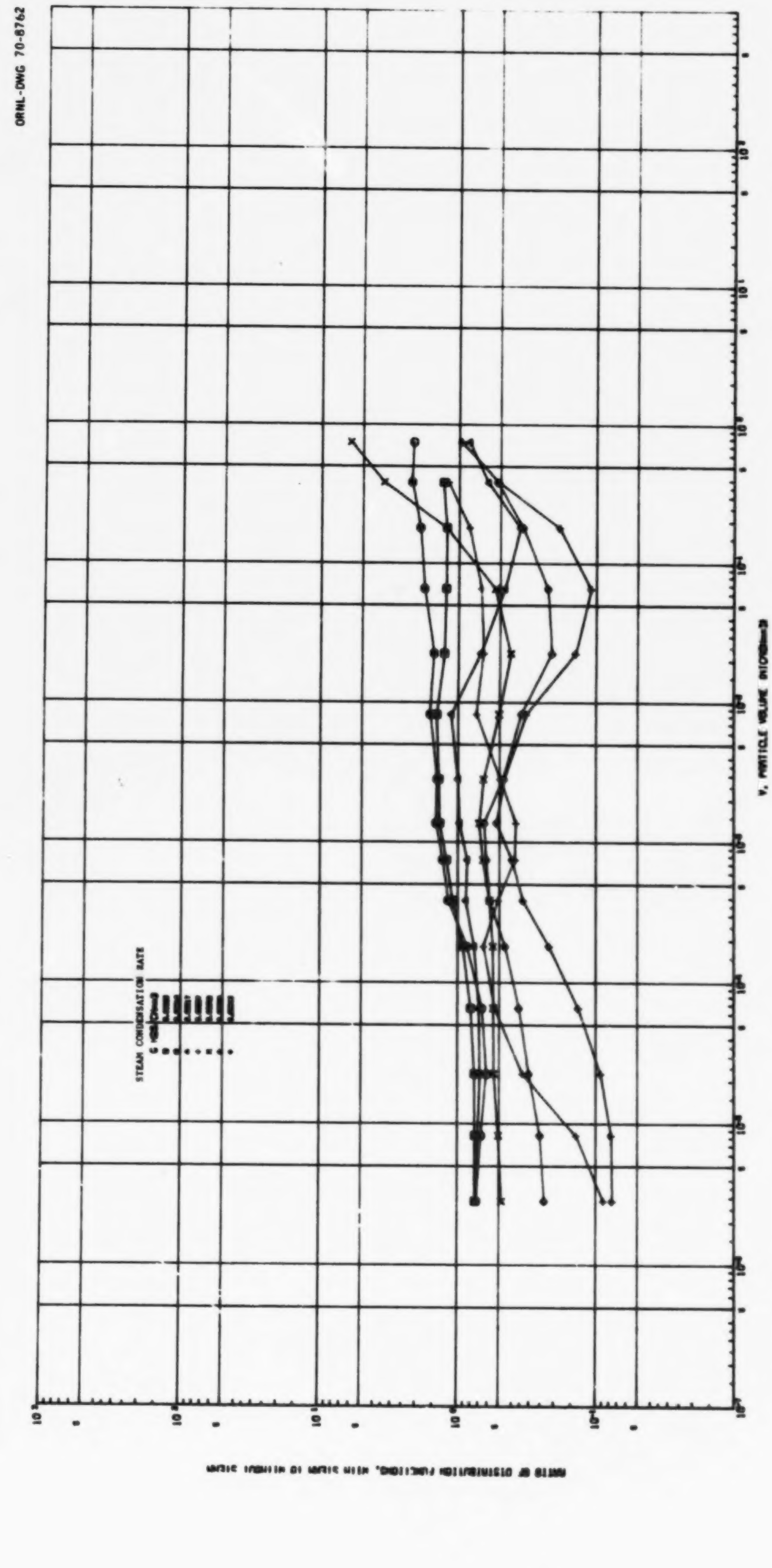


Figure 58. Dioctylphthalate, 0.1 Micron Mass Median Diameter, 7.6 x 10^4 particles/cm^3

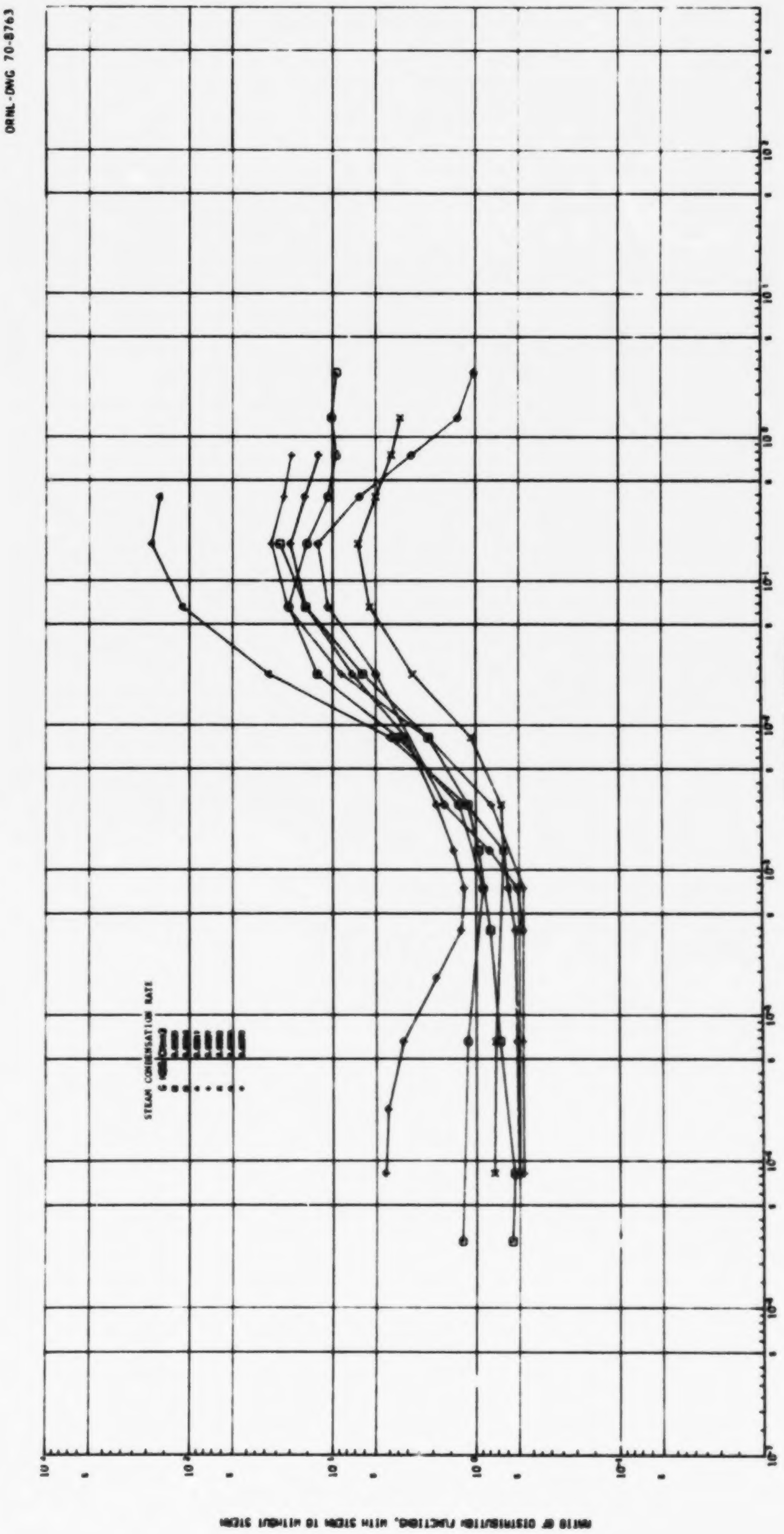


Figure 59. Dioctylphthalate, 0.05 Micron Mass Median Diameter, 1.9 x 10^4 particles/cm^3

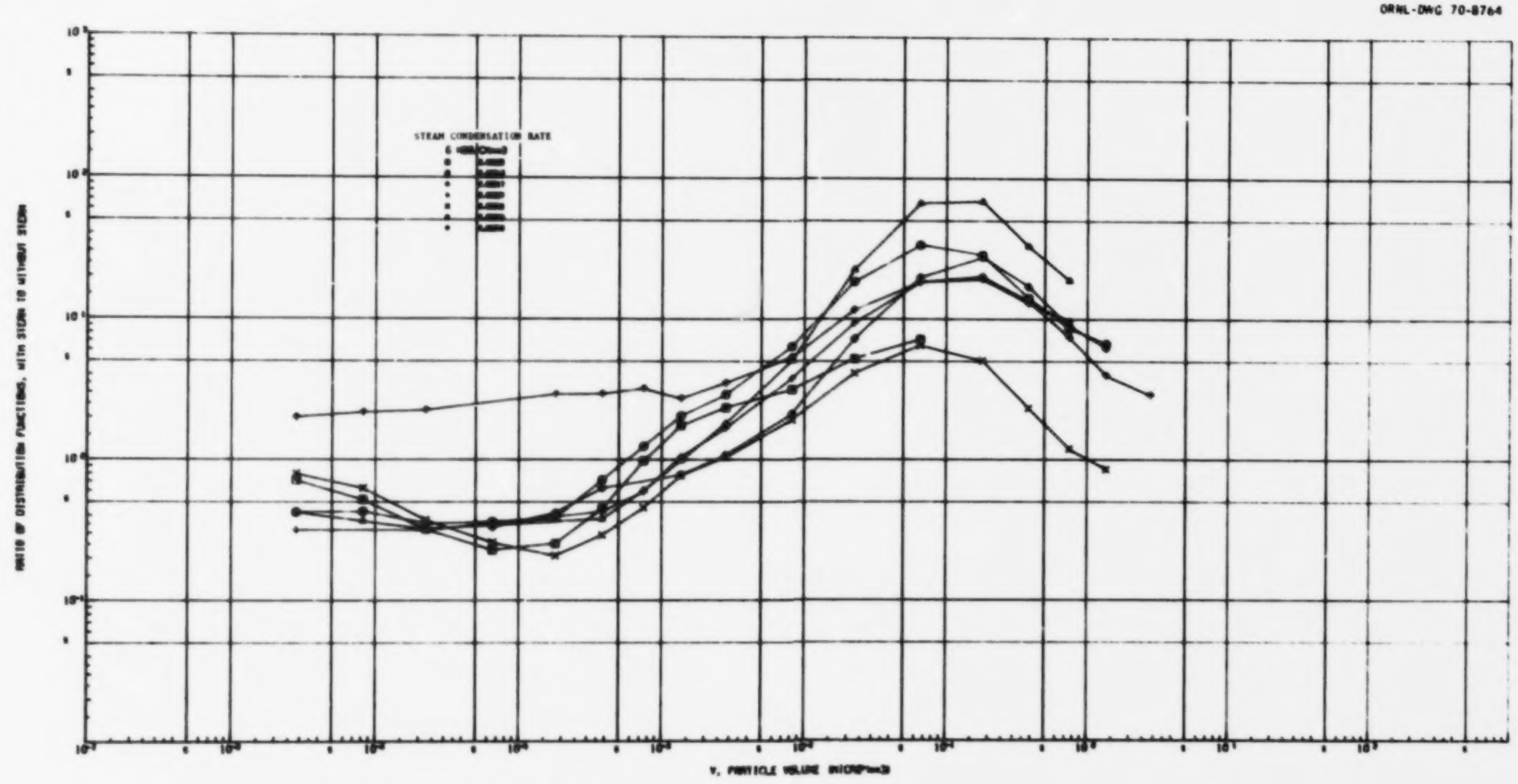


Figure 60. Dioctylphthalate, 0.05 Micron Mass Median Diameter, 3.8 x 10^4 particles/cm^3

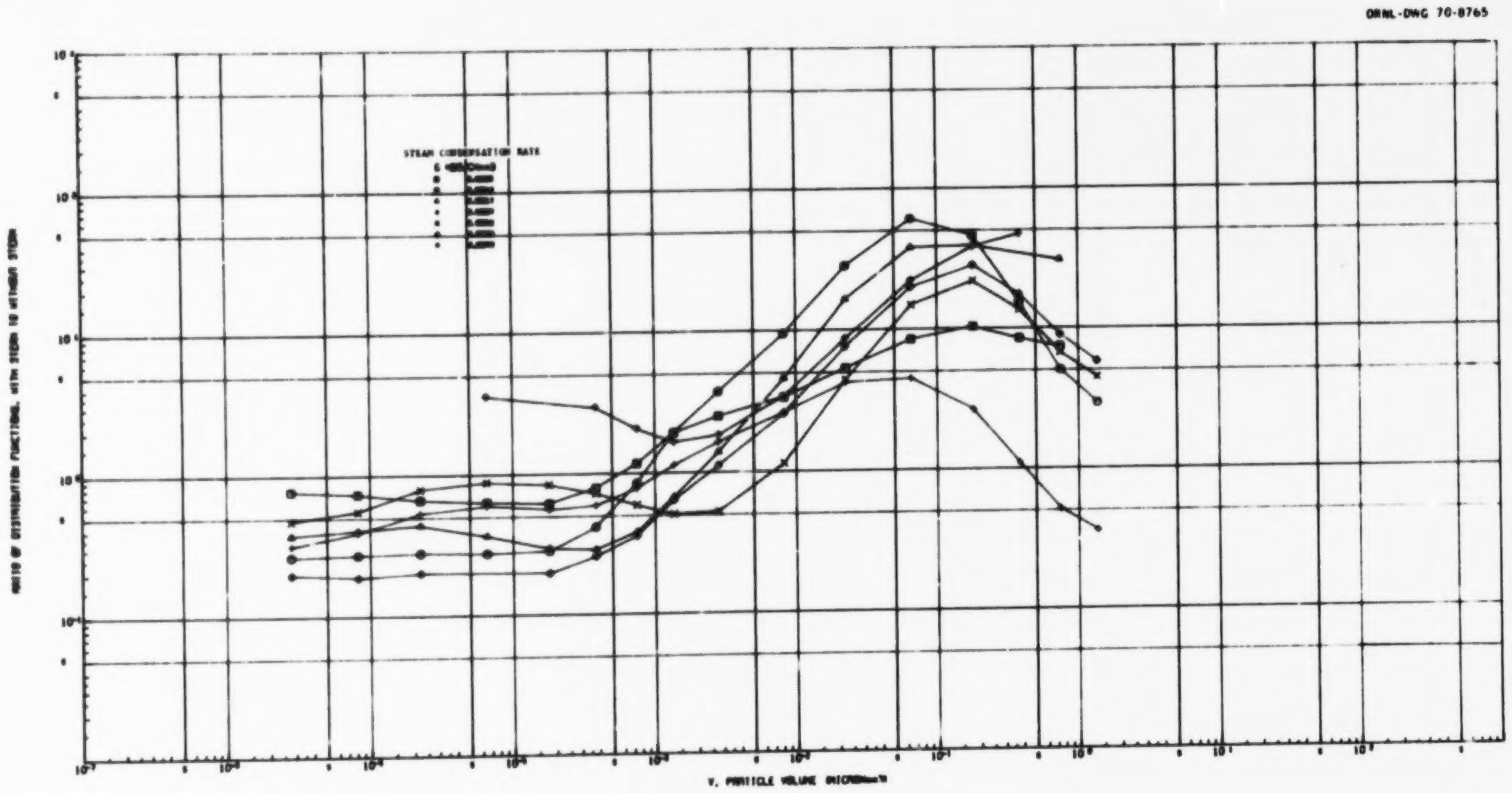


Figure 61. Dioctylphthalate, 0.05 Micron Mass Median Diameter, 5.7 x 10^4 particles/cm^3

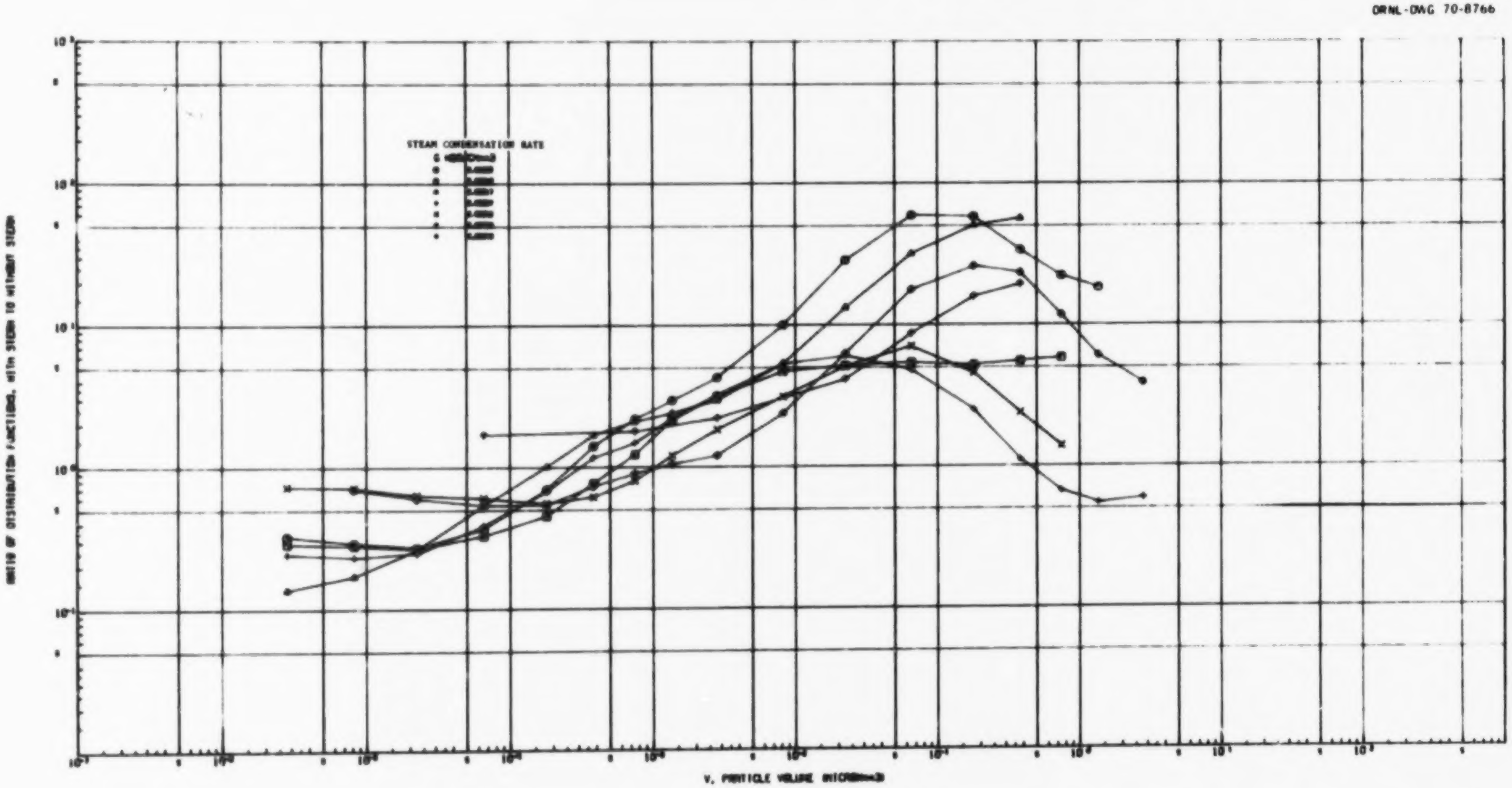


Figure 62. Dioctylphthalate, 0.05 Micron Mass Median Diameter, 7.6 x 10^4 particles/cm^3

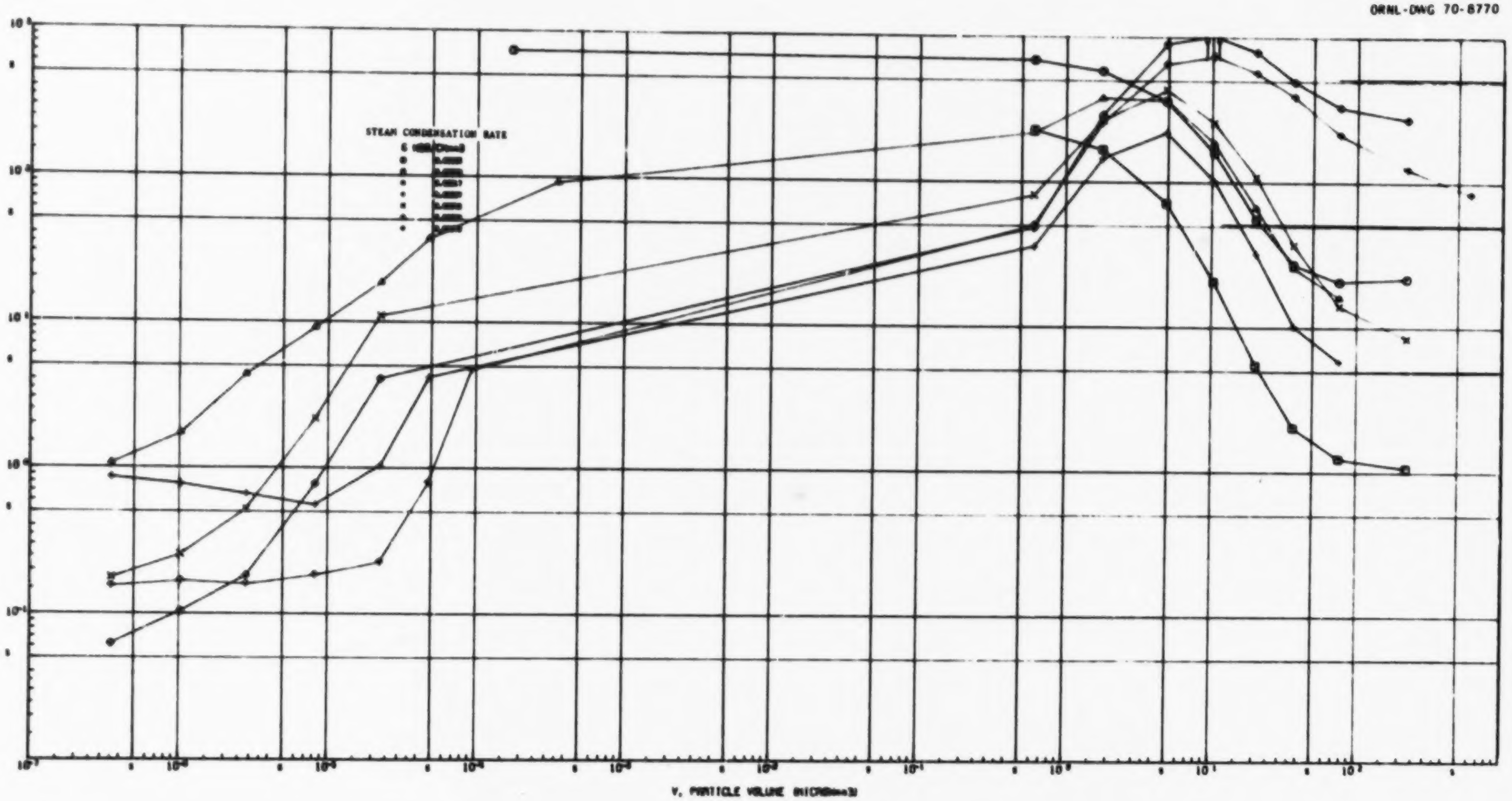


Figure 63. Stainless Steel Oxide, 0.007-15 Micron Diameter, 1.2 x 10^5 particles/cm^3

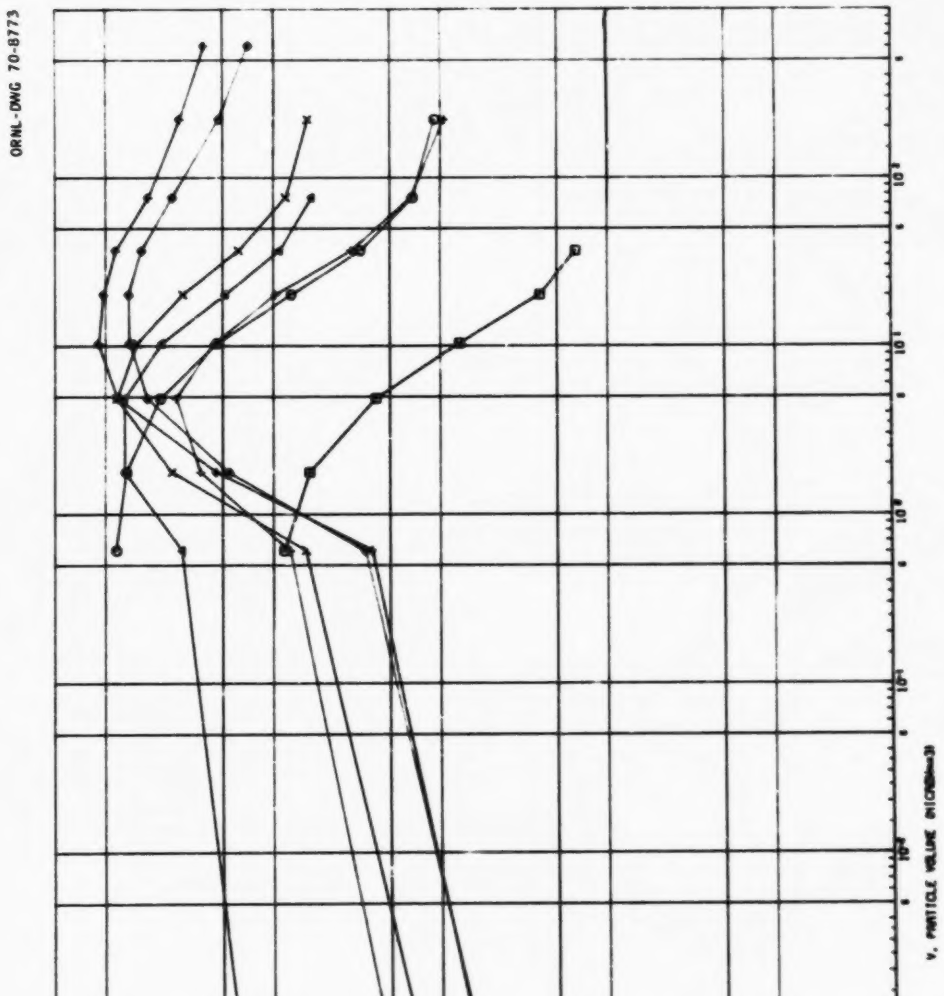


Figure 64. Stainless Steel Oxide, 0.007-15 Micron Diameter, 2.5×10^5 particles/cm^3

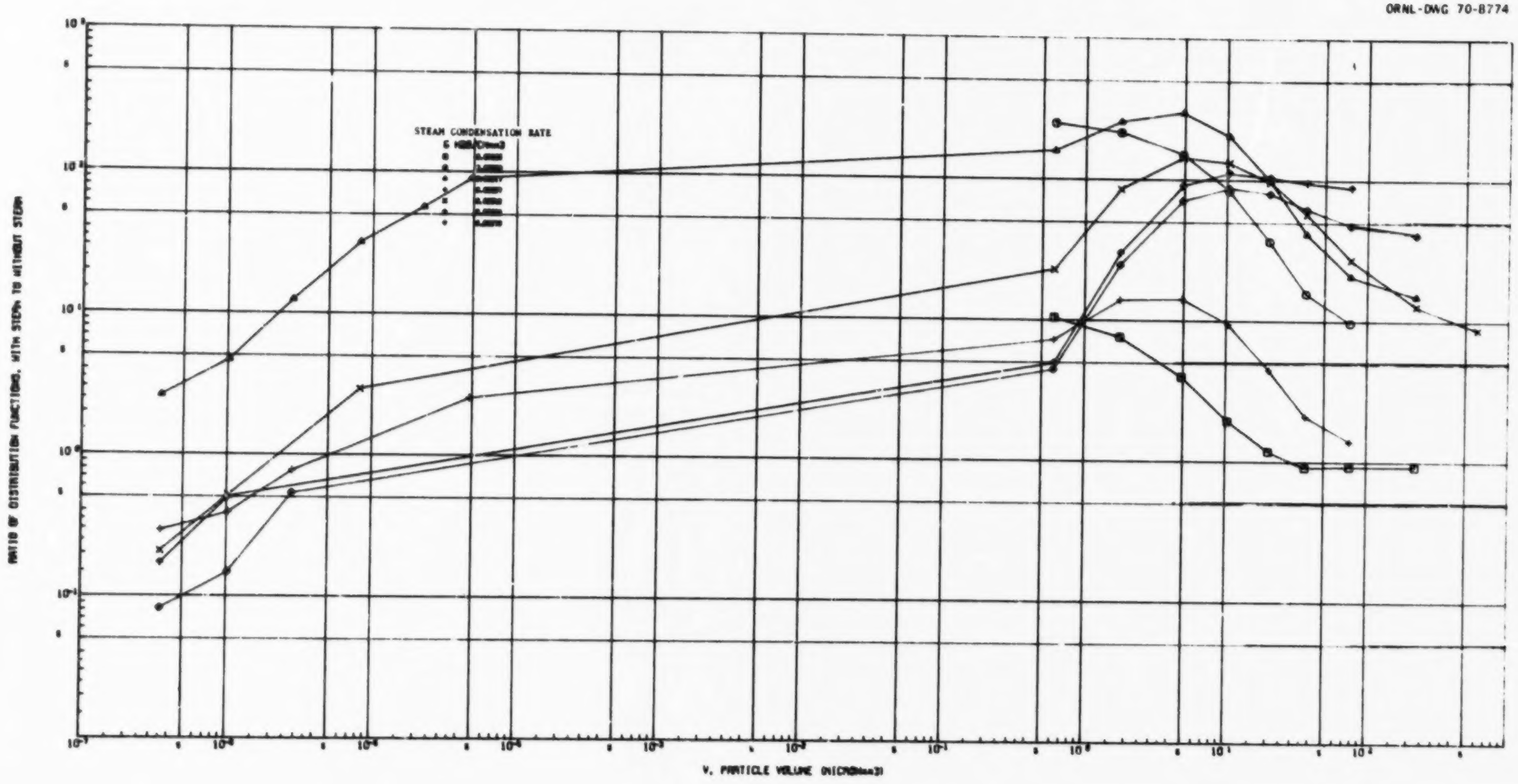


Figure 65. Stainless Steel Oxide, 0.007-15 Micron Diameter, 3.7 x 10^5 particles/cm^3

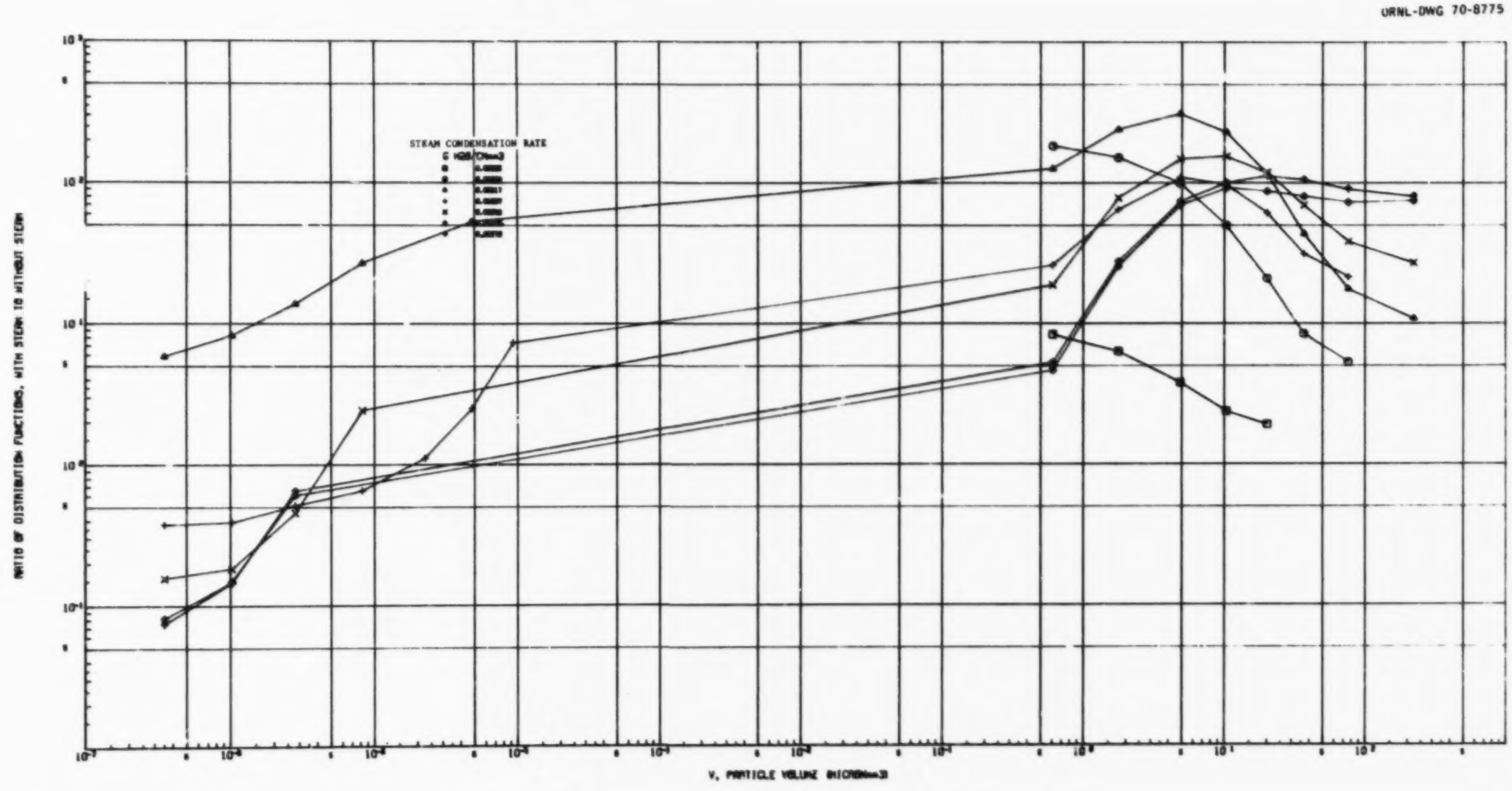


Figure 66. Stainless Steel Oxide, 0.007-15 Micron Diameter, 5.0 x 10^5 particles/cm^3

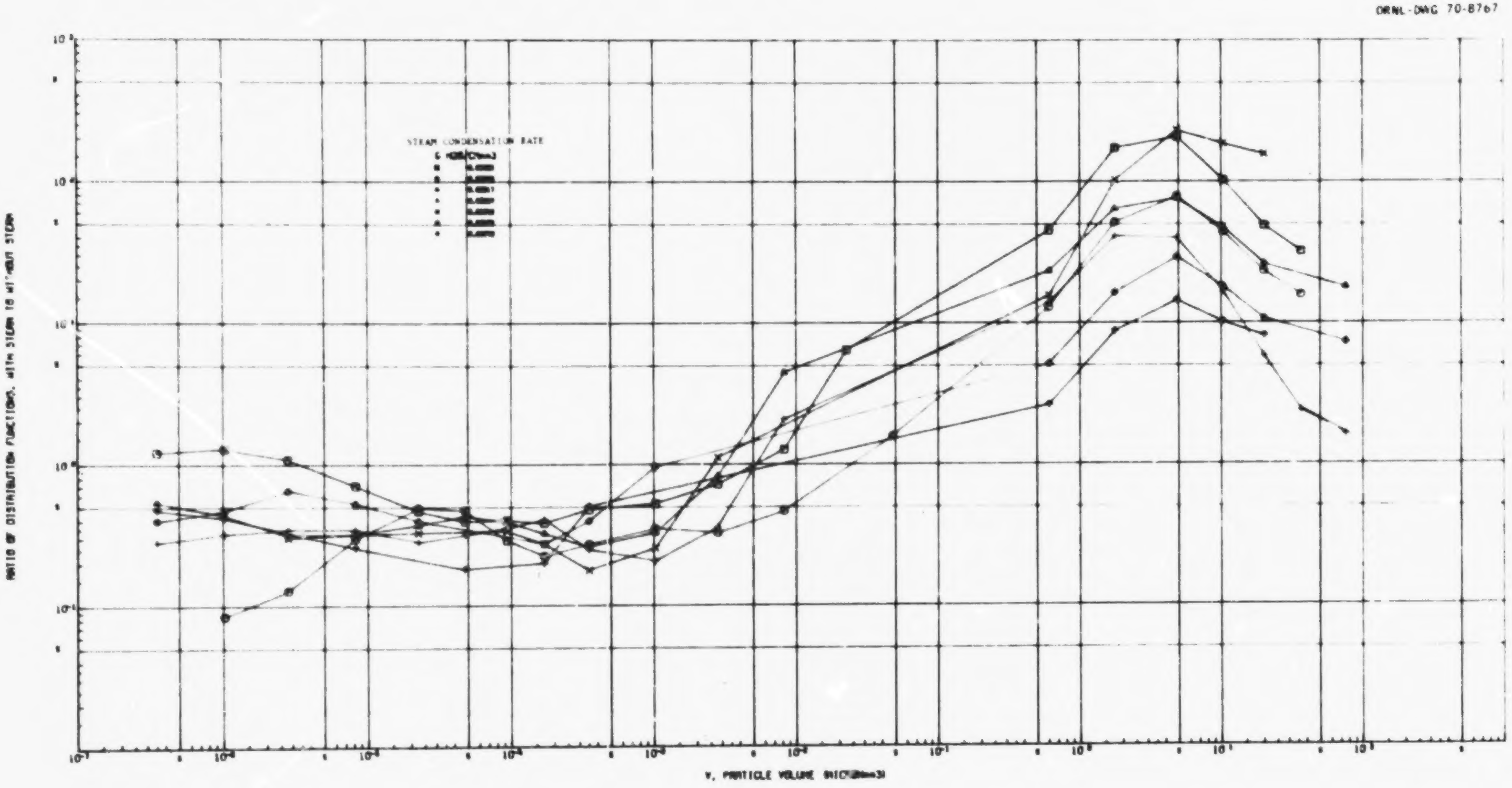


Figure 67. Stainless Steel Oxide, 0.015-6 Micron Diameter, 4.0 x 10^4 particles/cm^3

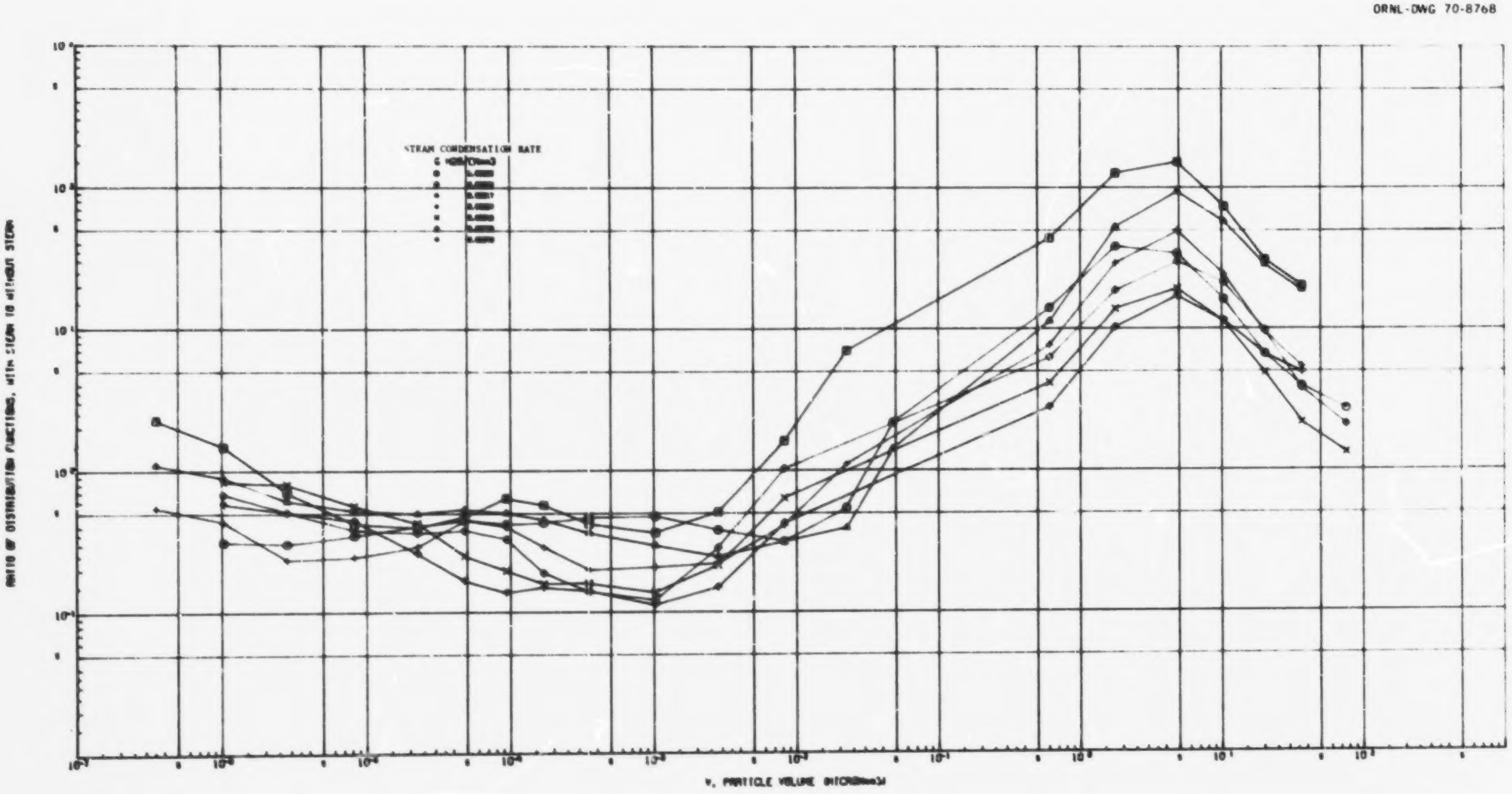


Figure 68. Stainless Steel Oxide, 0.015-6 Micron Diameter, 8.0 x 10^4 particles/cm^3

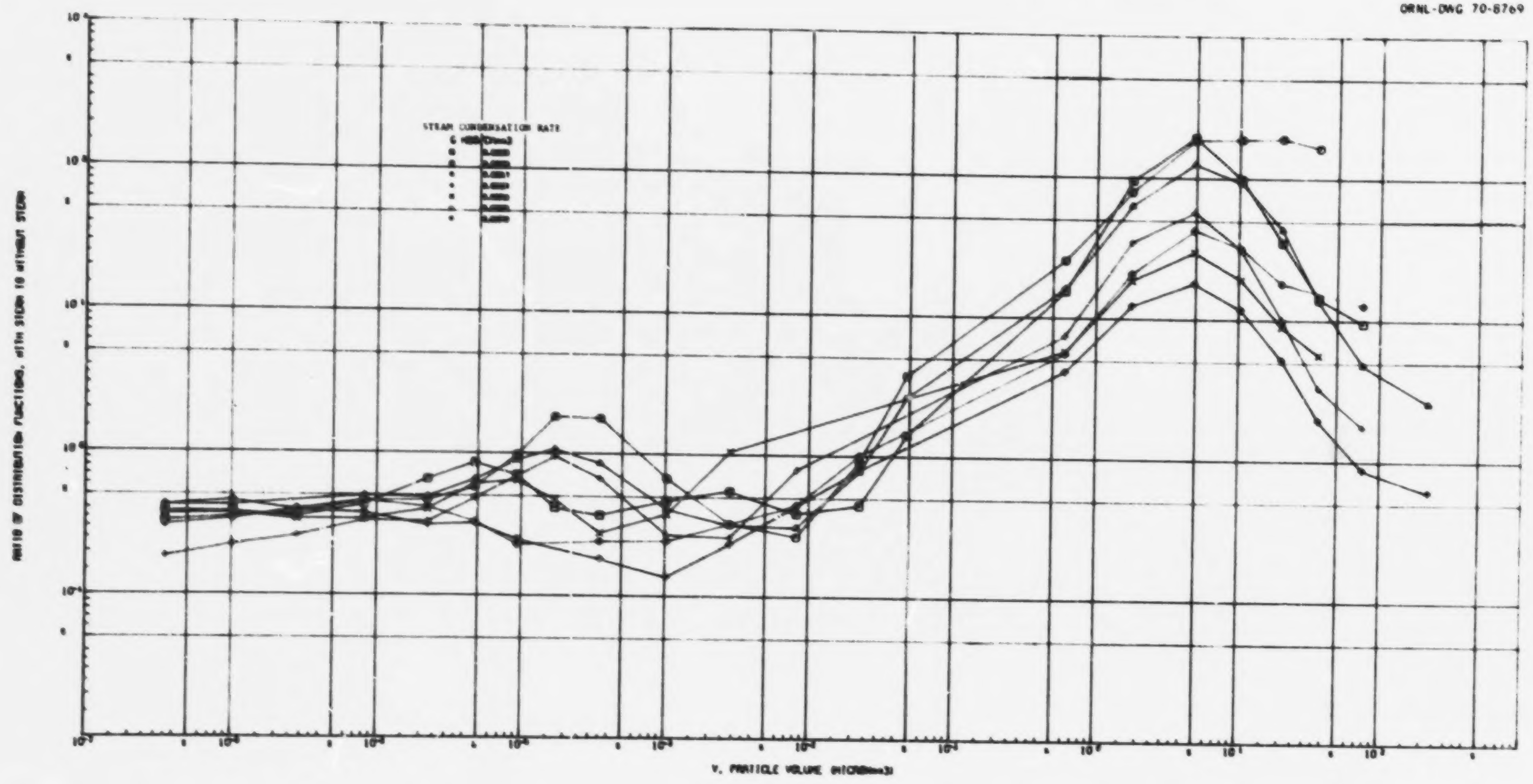


Figure 69. Stainless Steel Oxide, 0.015-6 Micron Diameter, 1.2 x 10^5 particles/cm^3

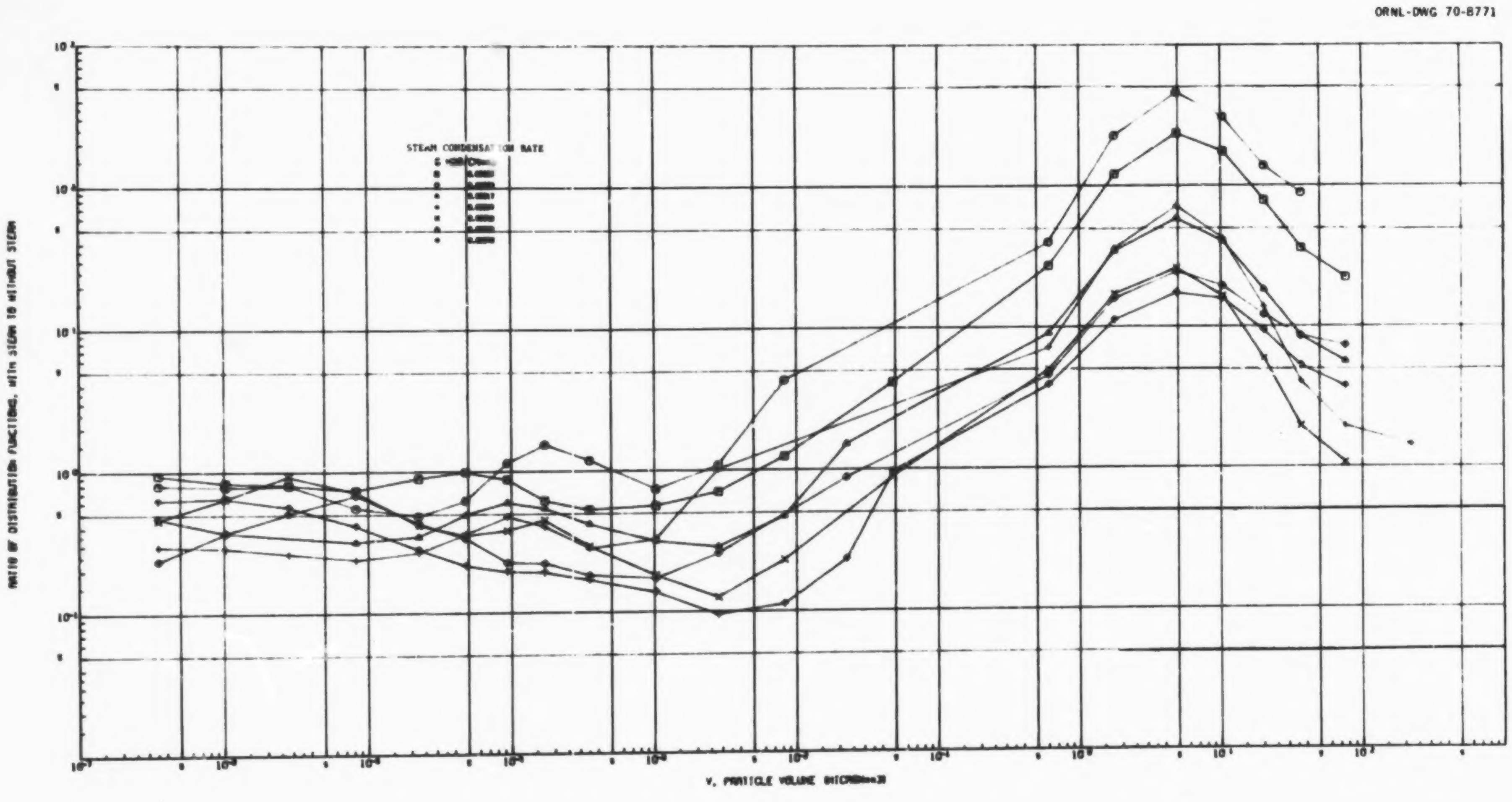


Figure 70. Stainless Steel Oxide, 0.015-6 Micron Diameter, 1.6 x 10^5 particles/cm^3

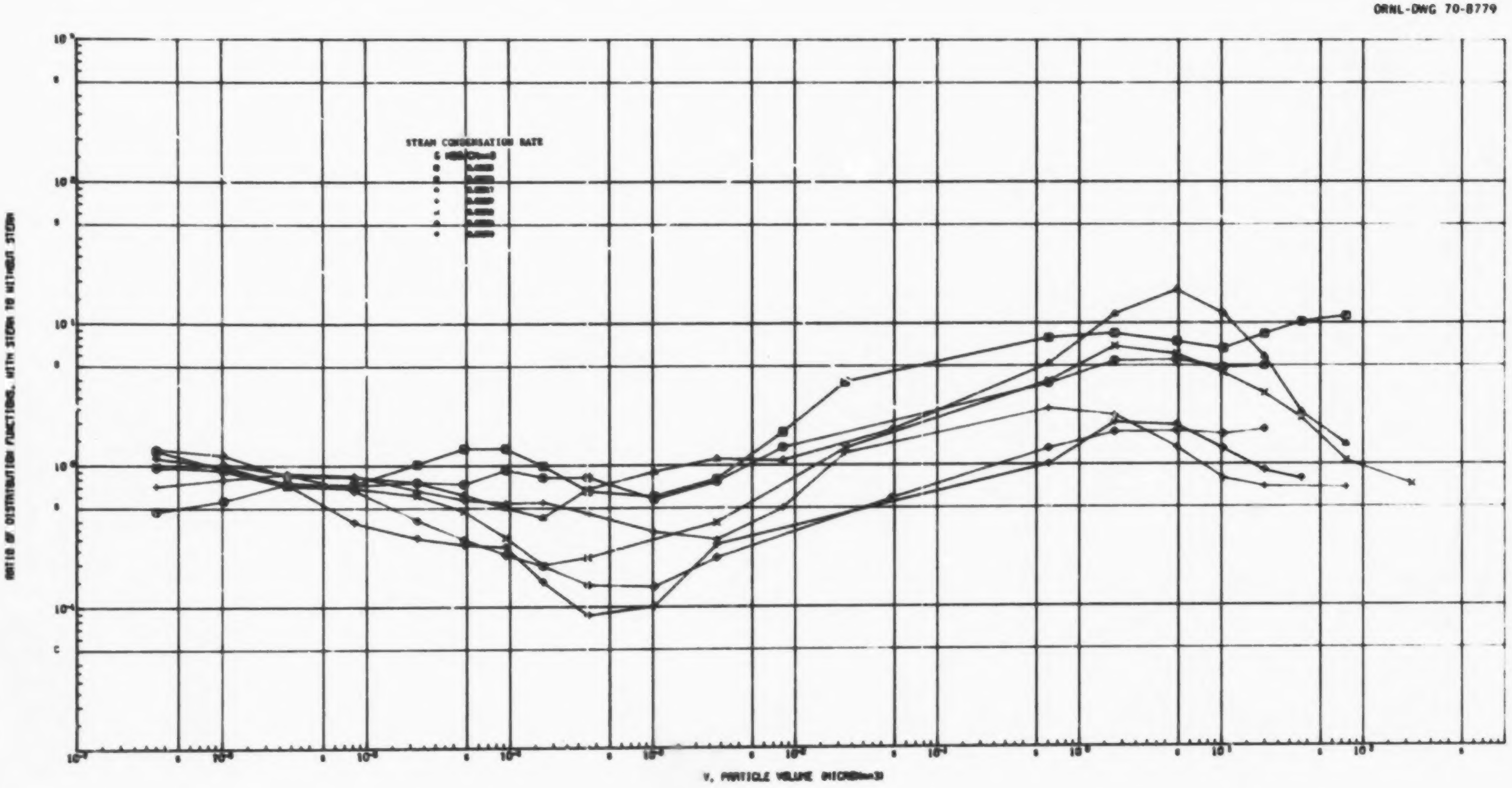


Figure 71. Iron Oxide, 0.015-6 Micron Diameter, 1.2 x 10^5 particles/cm^3

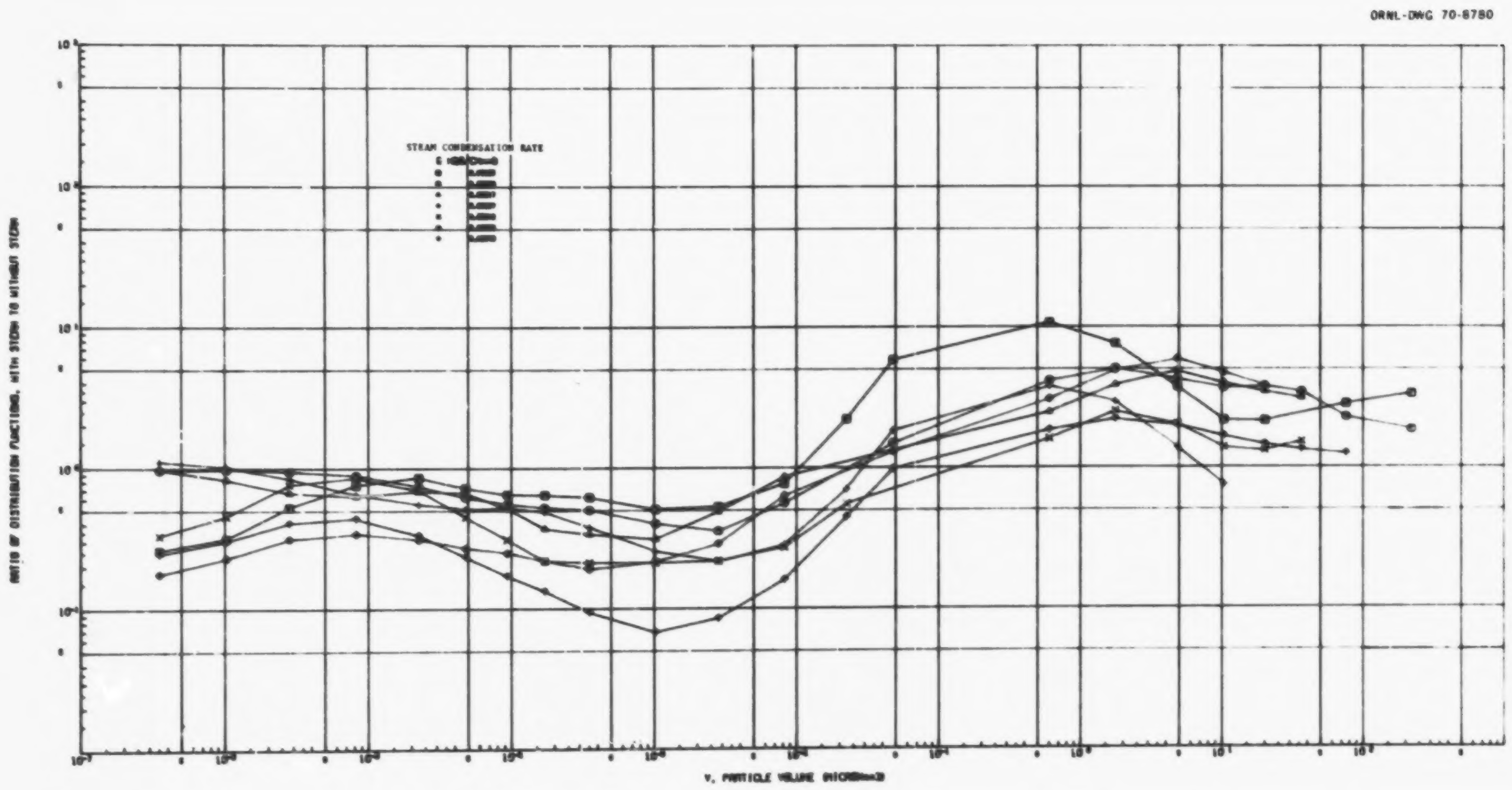


Figure 72. Iron Oxide, 0.015-6 Micron Diameter, 2.5 x 10^5 particles/cm^3

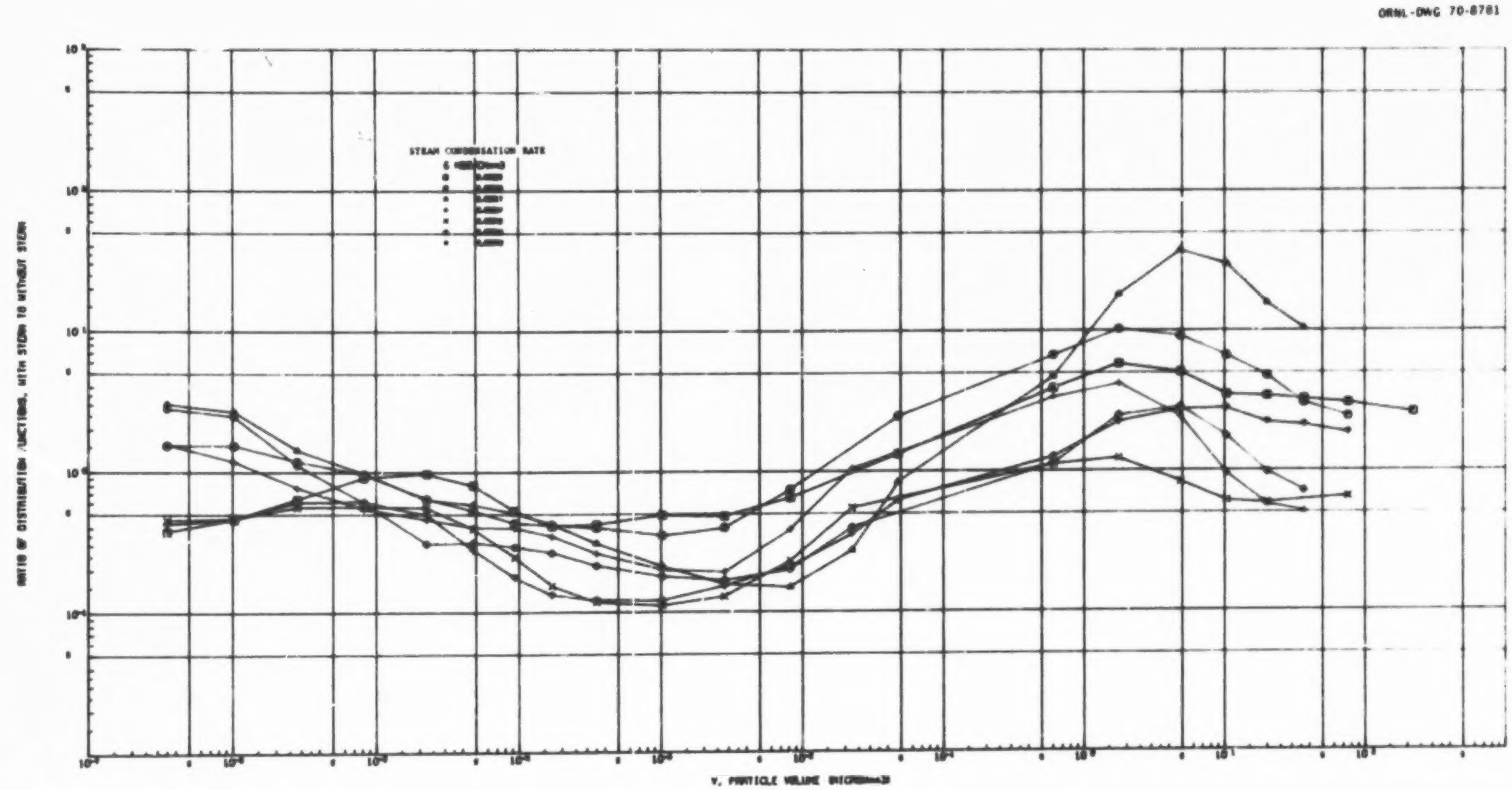


Figure 73. Iron Oxide, 0.015-6 Micron Diameter, 3.7 x 10^5 particles/cm^3

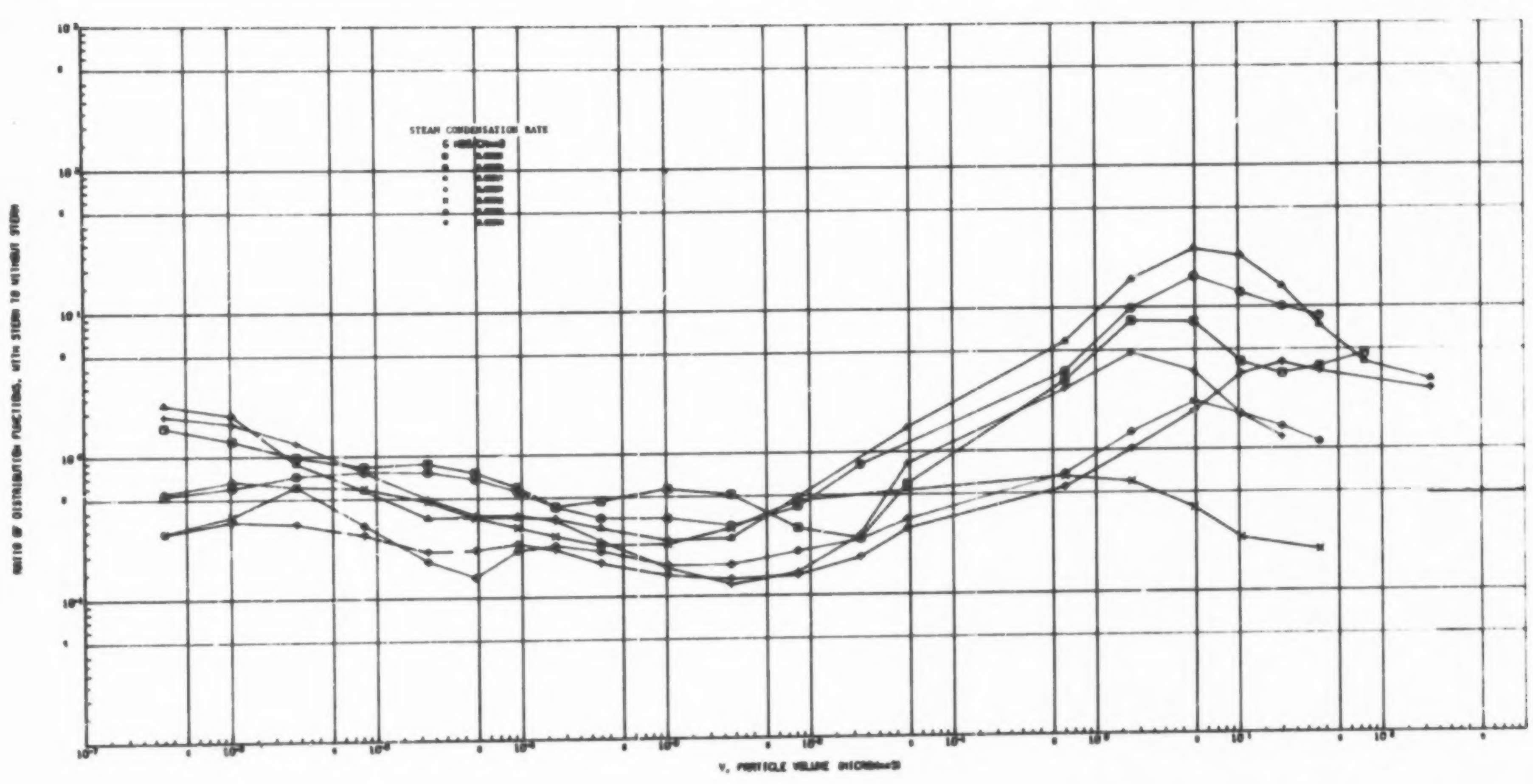


Figure 74. Iron Oxide, 0.015-6 Micron Diameter, 5.0 x 10^5 particles/cm^3

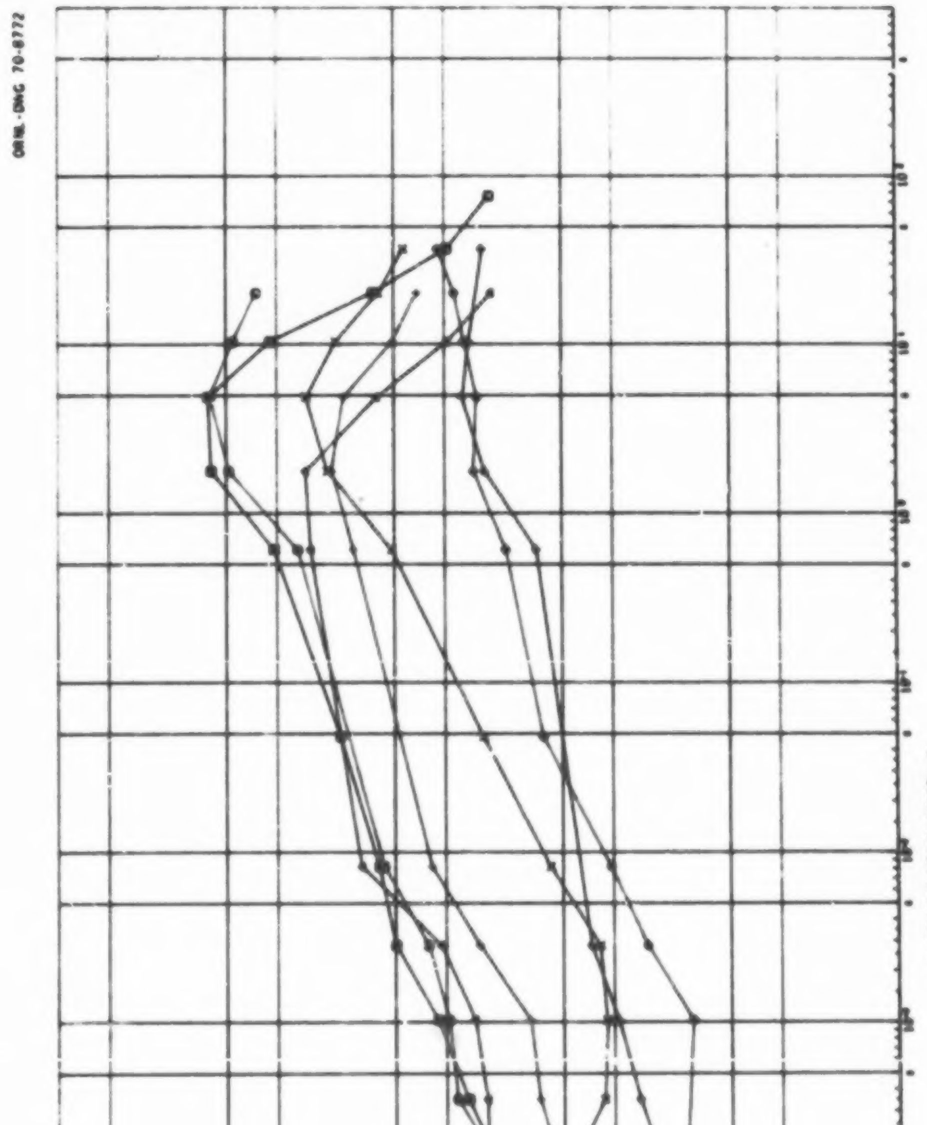


Figure 75. Chromium Oxide, 0.012-7 Micron Diameter, 4.0 x 10^4 particles/cm^3

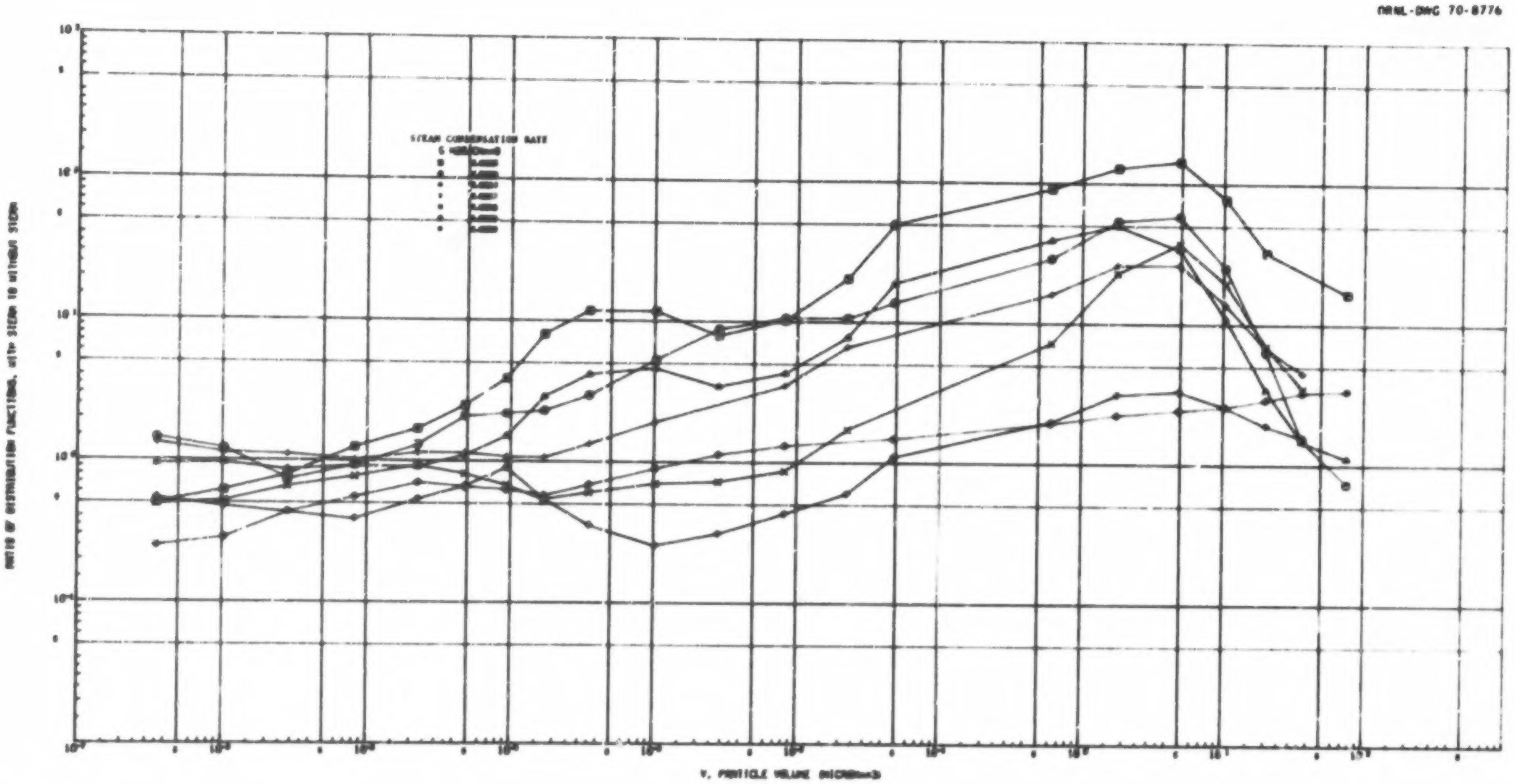


Figure 76. Chromium Oxide, 0.012-7 Micron Diameter, 8.0 x 10^4 particles/cm^3

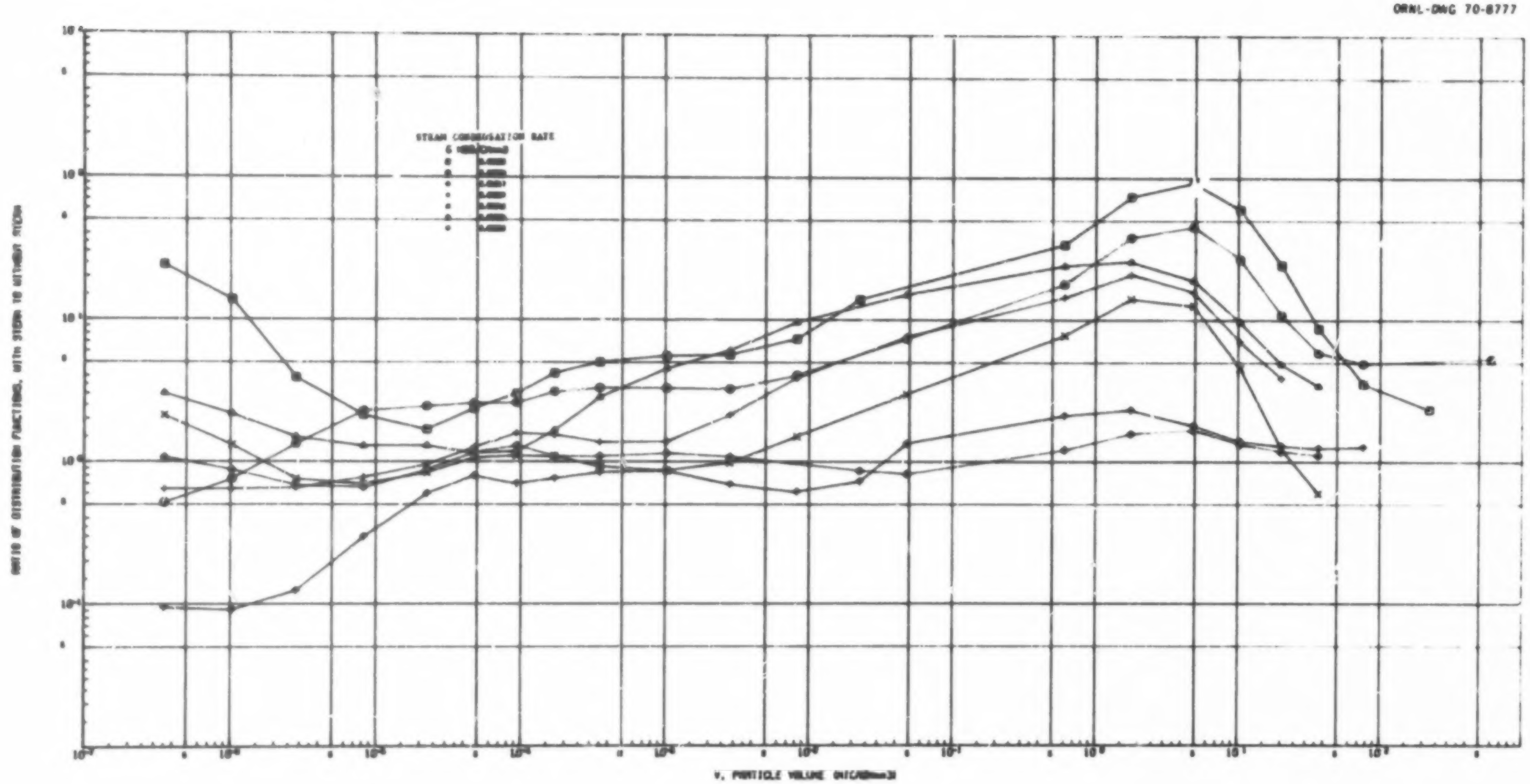


Figure 77. Chromium Oxide, 0.012-7 Micron Diameter, 1.2 x 10^5 particles/cm^3

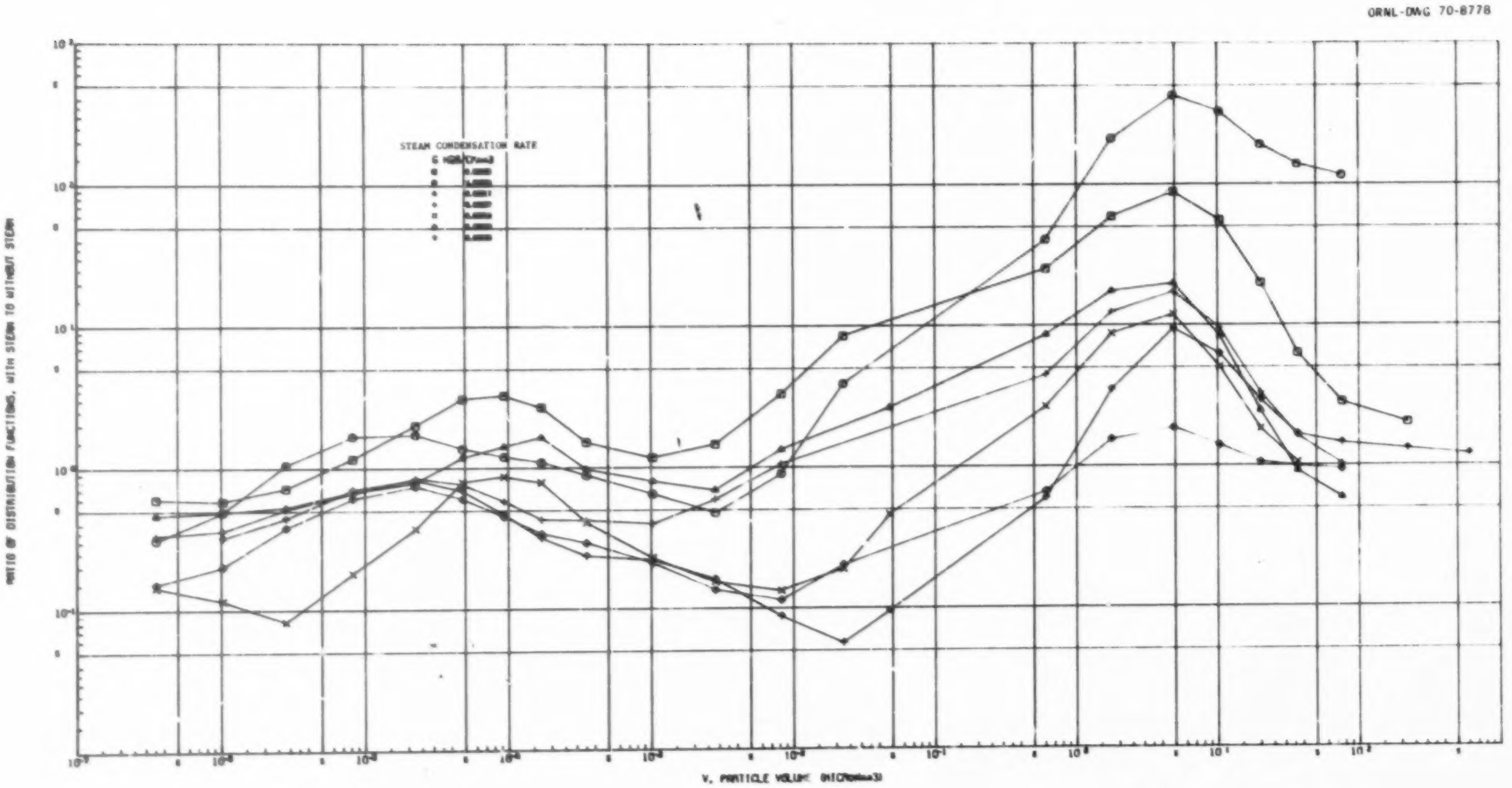


Figure 78. Chromium Oxide, 0.012-7 Micron Diameter, 1.6 x 10^5 particles/cm^3

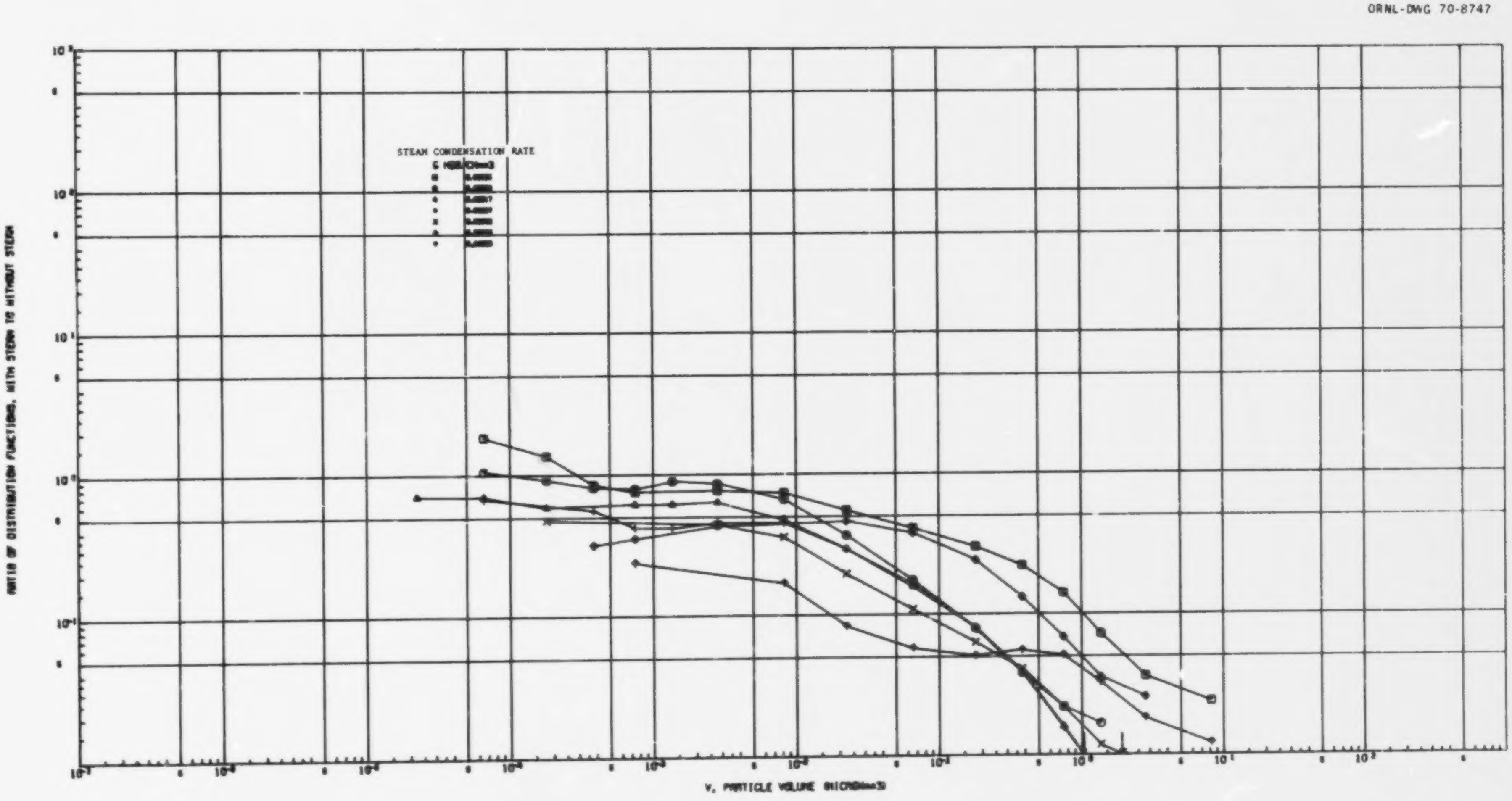


Figure 79. Ammonium Chloride, 0.06-13 Micron Diameter, 1.3 x 10^6 particles/cm^3

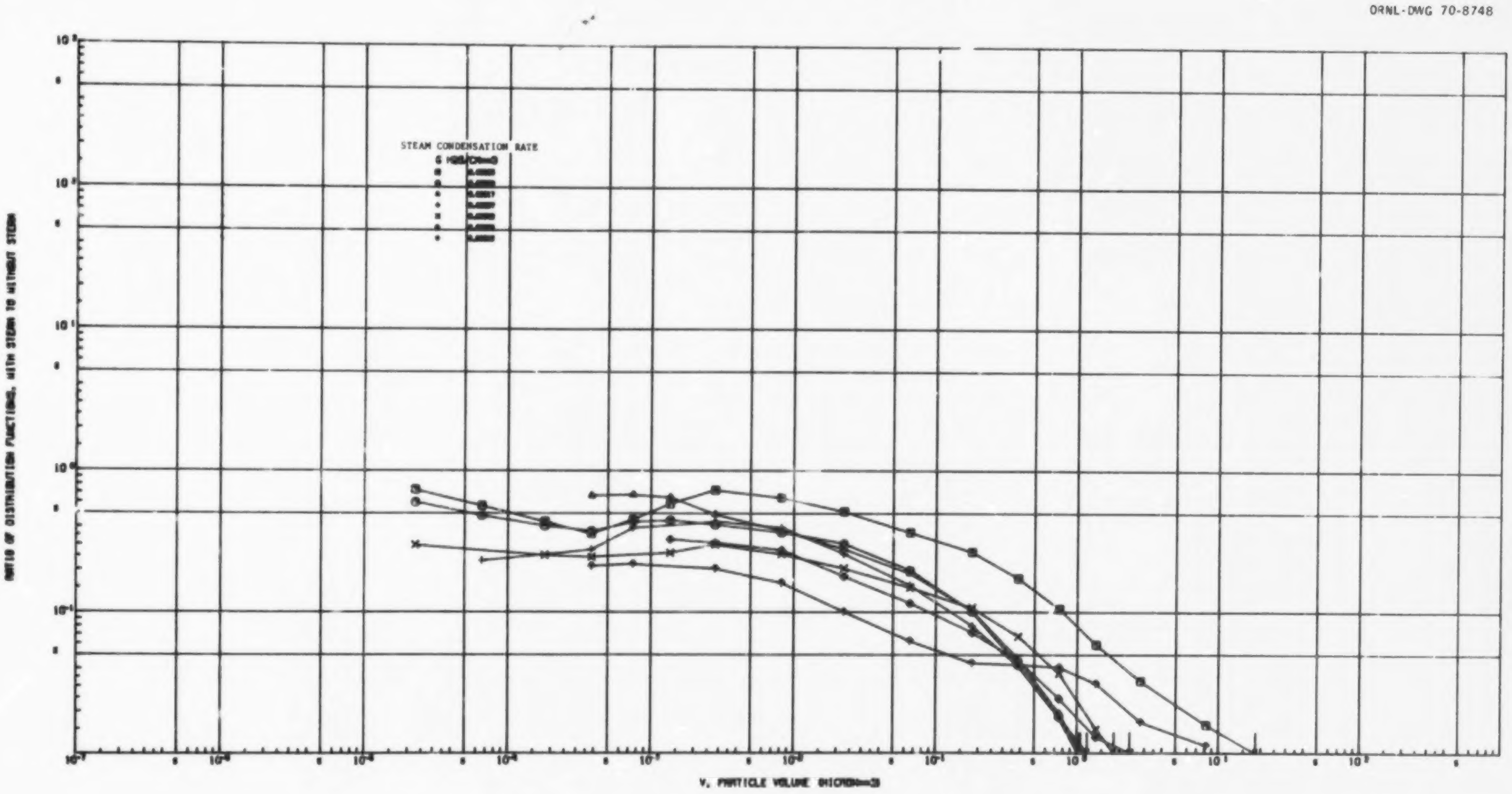


Figure 80. Ammonium Chloride, 0.06-13 Micron Diameter, 2.7 x 10^6 particles/cm^3

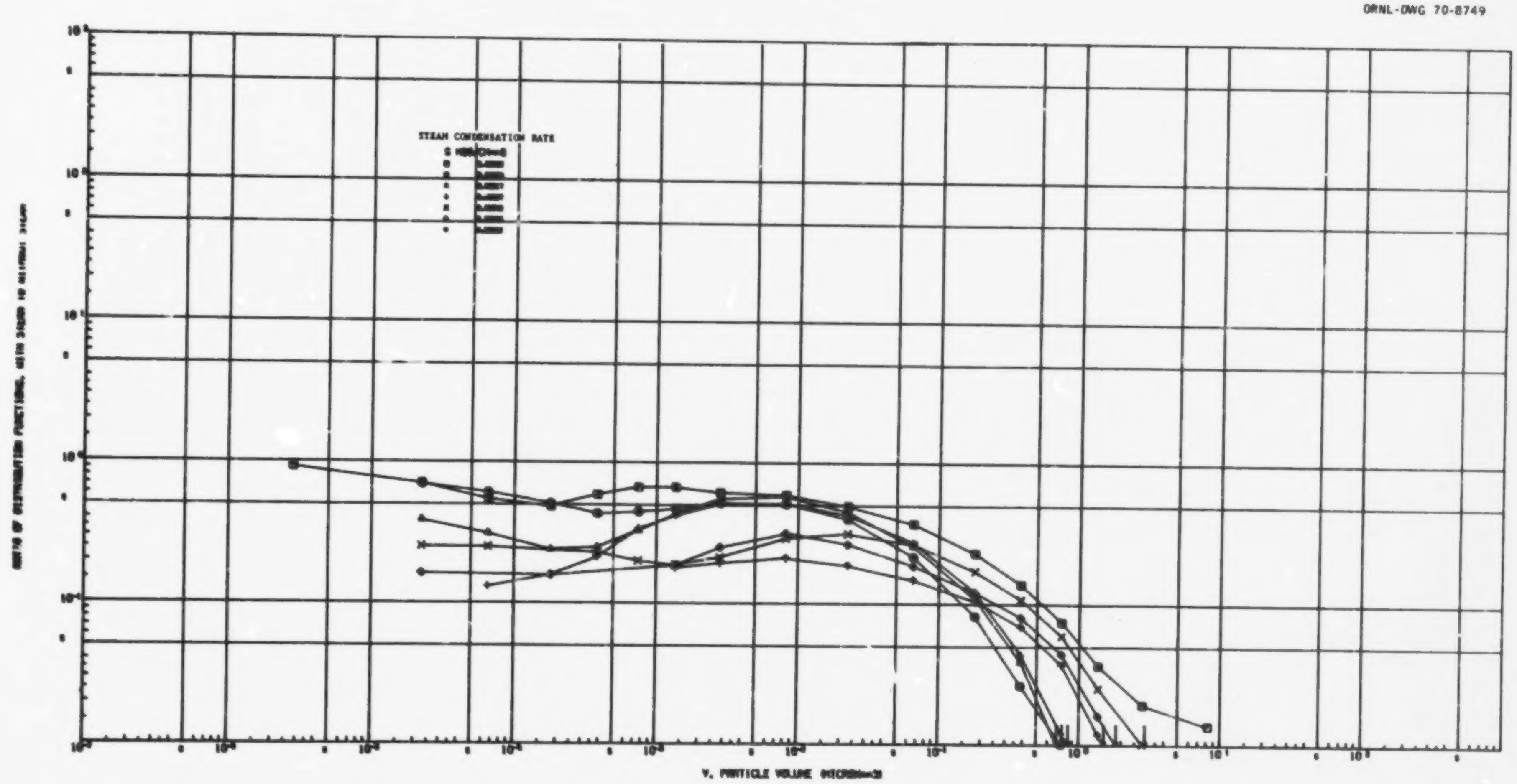


Figure 81. Ammonium Chloride, 0.06-13 Micron Diameter, 4.0 x 10^6 particles/cm^3

ORNL-DWG 70-8750

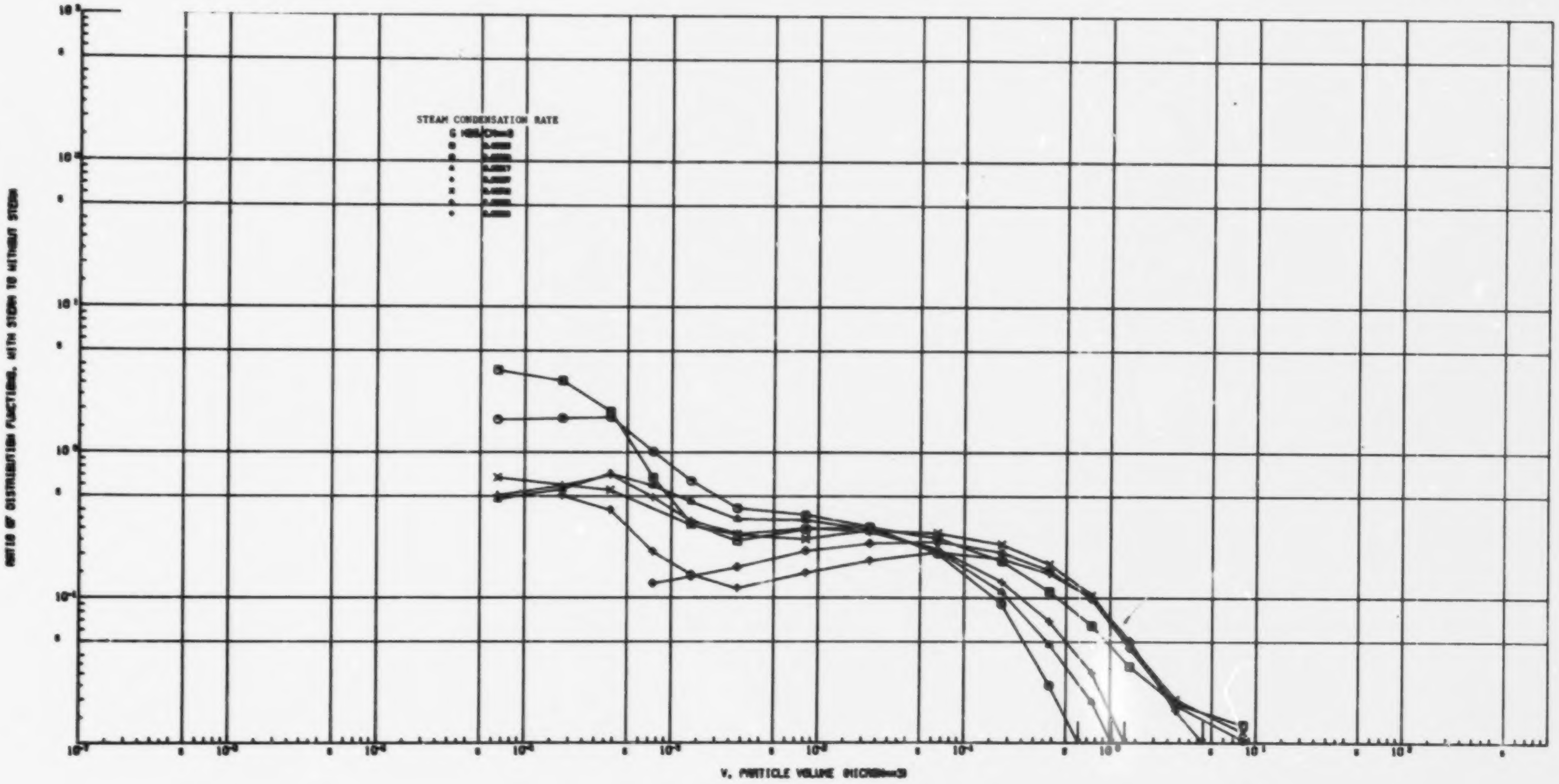


Figure 82. Ammonium Chloride, 0.06-13 Micron Diameter, 5.4 x 10^6 particles/cm^3

ORNL-DWG 70-10330

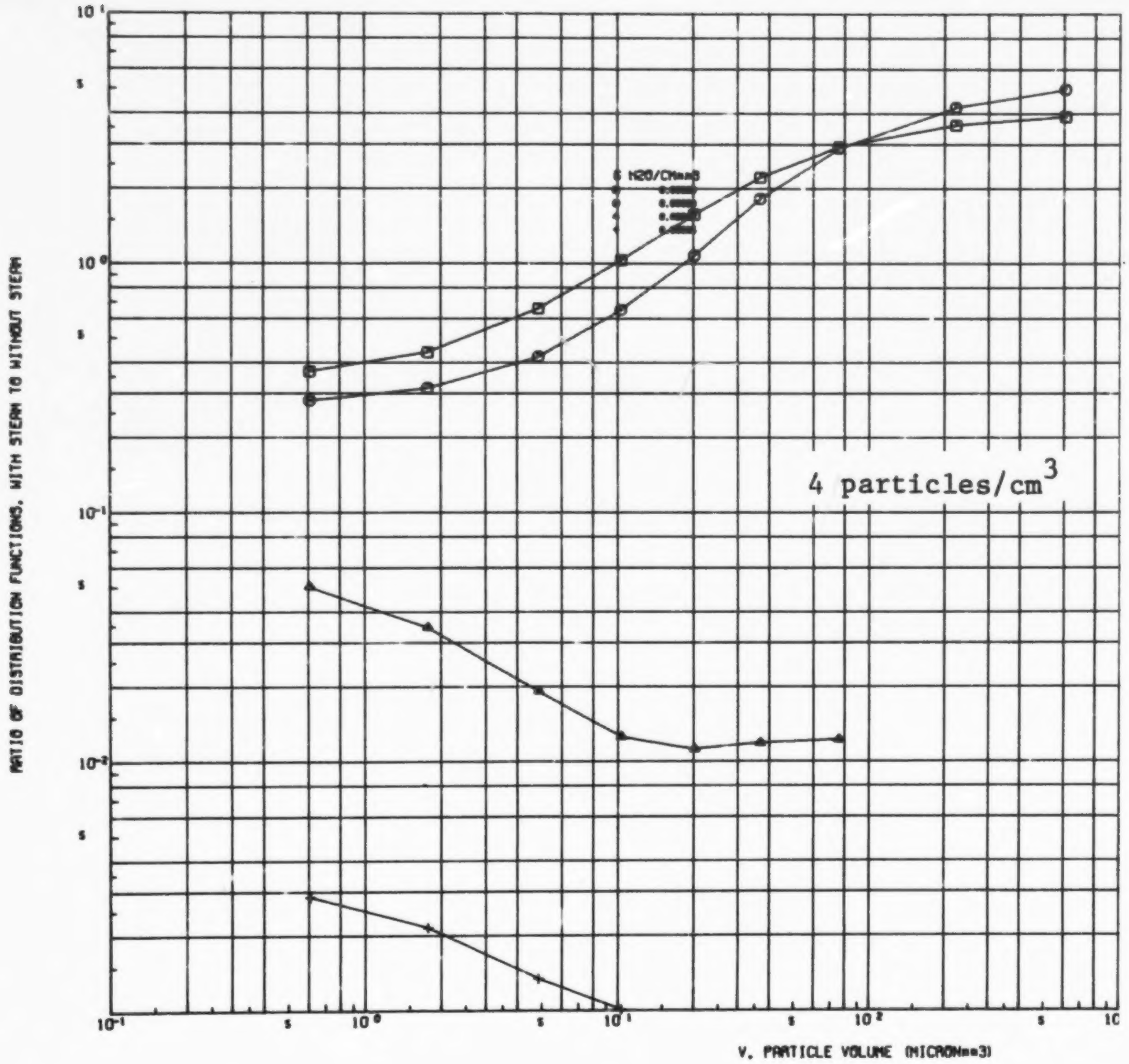


Figure 83. Methylene Blue, 2 Micron

ORNL-DWG 70-10331

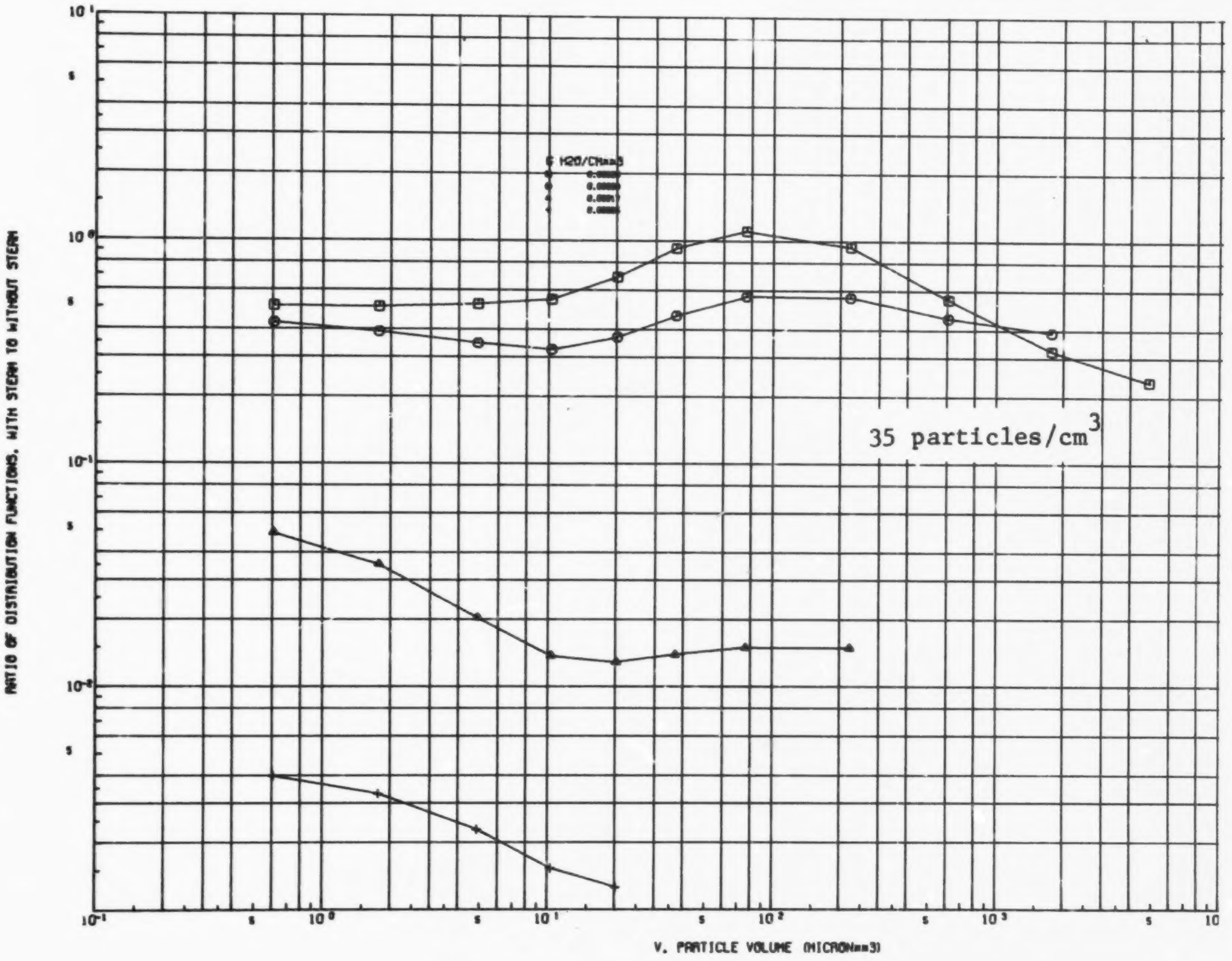


Figure 84. Methylene Blue, 2.7 Micron

ORNL-DWG 70-10332

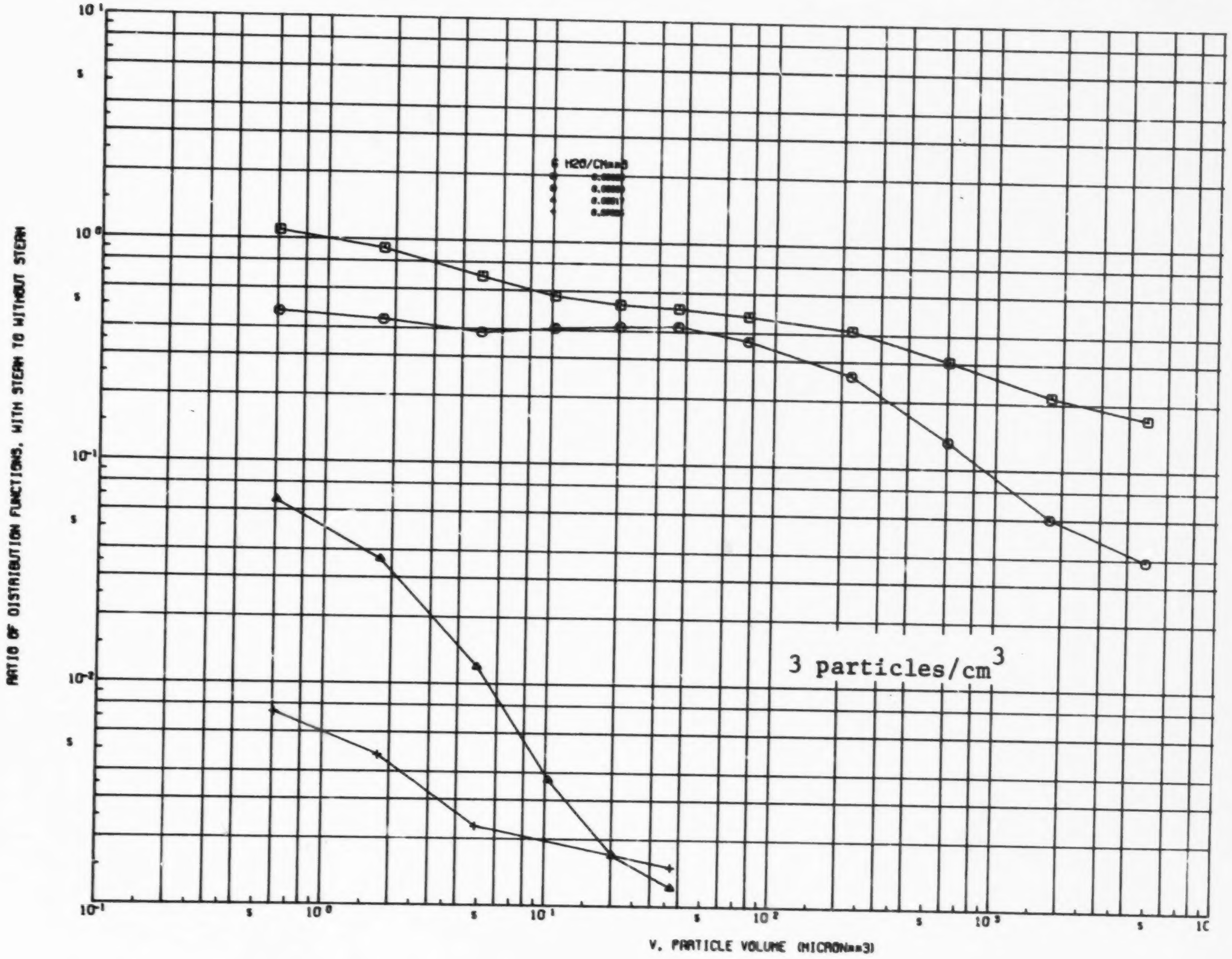


Figure 85. Methylene Blue, 4 Micron

is noted on the top of each figure. For the methylene blue particles only one concentration was tested, hence one graph for each particle size. We will put off discussion of these results until the next section.

So Figs. 35-85 show one kind of experimental result, namely the dependence of particle size distribution on steam condensation rate, particle size, substance and concentration. The other kind of experimental result was the total number concentration; these are presented as semi-log plots of the ratios of number concentration of the effluent aerosol with steam condensation to the corresponding concentration without steam, the log of the ratio plotted against steam condensation rate (g H_2O/cm^3 aerosol) (this kind of plot is similar to the plots of theoretically derived values on Figs. 16 and 17). These number concentration ratios vs steam condensation rate appear on Figs. 86-100. Each graph refers to a particle substance and size (or size range); a separate curve appears for each inlet concentration employed.

So the nature of most of the data are indicated on Table 1 and on Figs. 33 and 34. Two kinds of results are presented: size distribution ratios (wet to dry) vs particle size and steam condensation rate are given on Figs. 35-85 and number concentration ratios are given on Figs. 86-100.

A special series of tests was done to suggest the effect of velocity in the condenser. In this series stainless steel oxide aerosol as described in Fig. 26 was used. A sequence of aerosol, air and air plus steam feeds were used to maintain the dilution at the inlet constant as follows:

Aerosol Feed (liters/min)	Dilution Air (liters/min)	Air Plus Steam (liters/min)
0.5	0	8
0.75	4	8
1.	8	8
1.5	16	8
2.	24	8

As in the other experiments a sequence of pairs of tests was run; one without steam and one with steam, each member of the sequence at a different steam condensation rate. Only the number concentrations were measured. The results are shown on Fig. 101 as a semi-log plot of number concentration ratio (wet to dry) vs steam condensation rate. The inlet number concentration, N_o, was about 4×10^5 particles/cm^3.

ORNL-DWG 70-8475

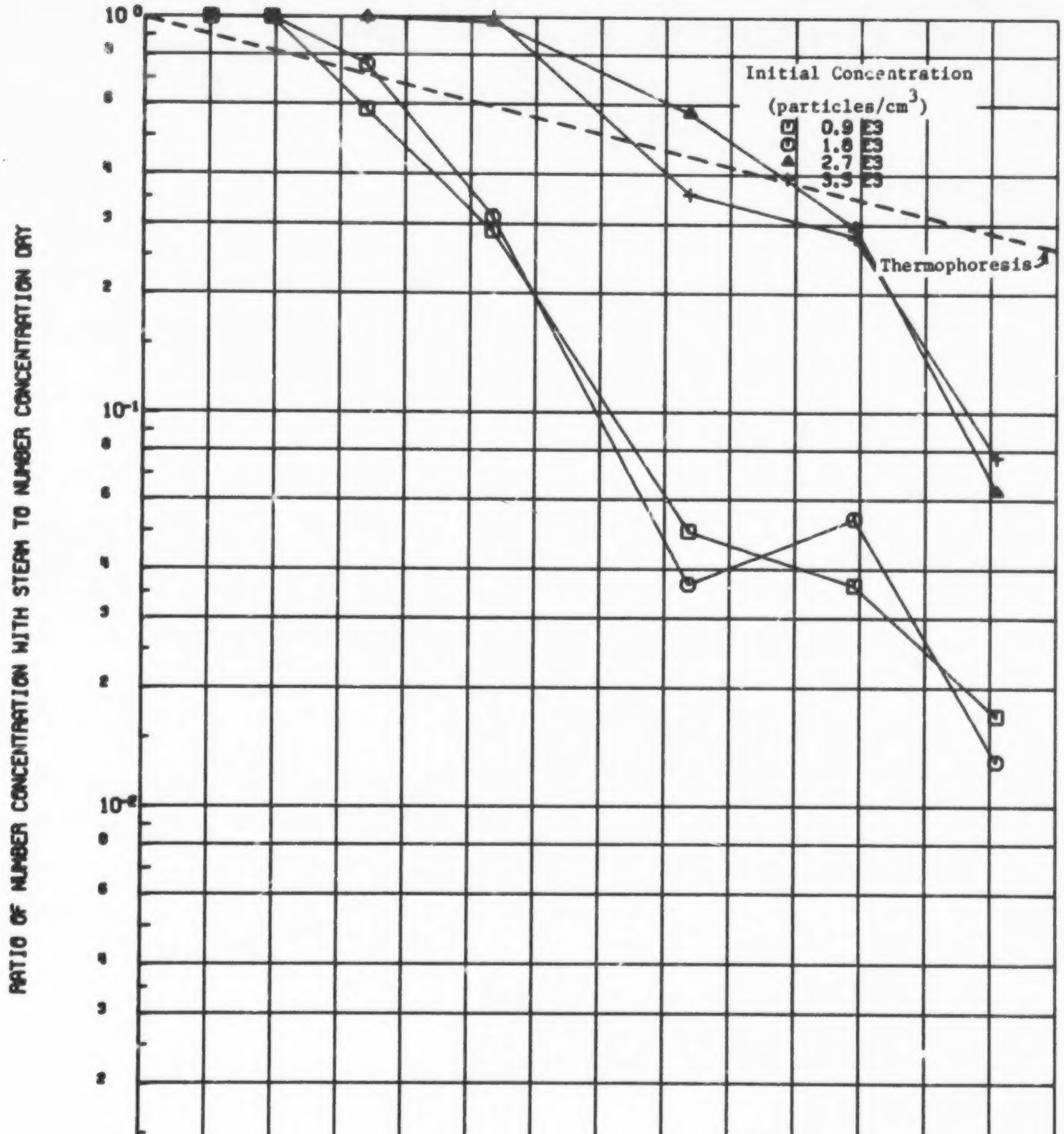


Figure 86. Latex, 1.9 Micron Mass Median Diameter

ORNL-DWG 70-8478

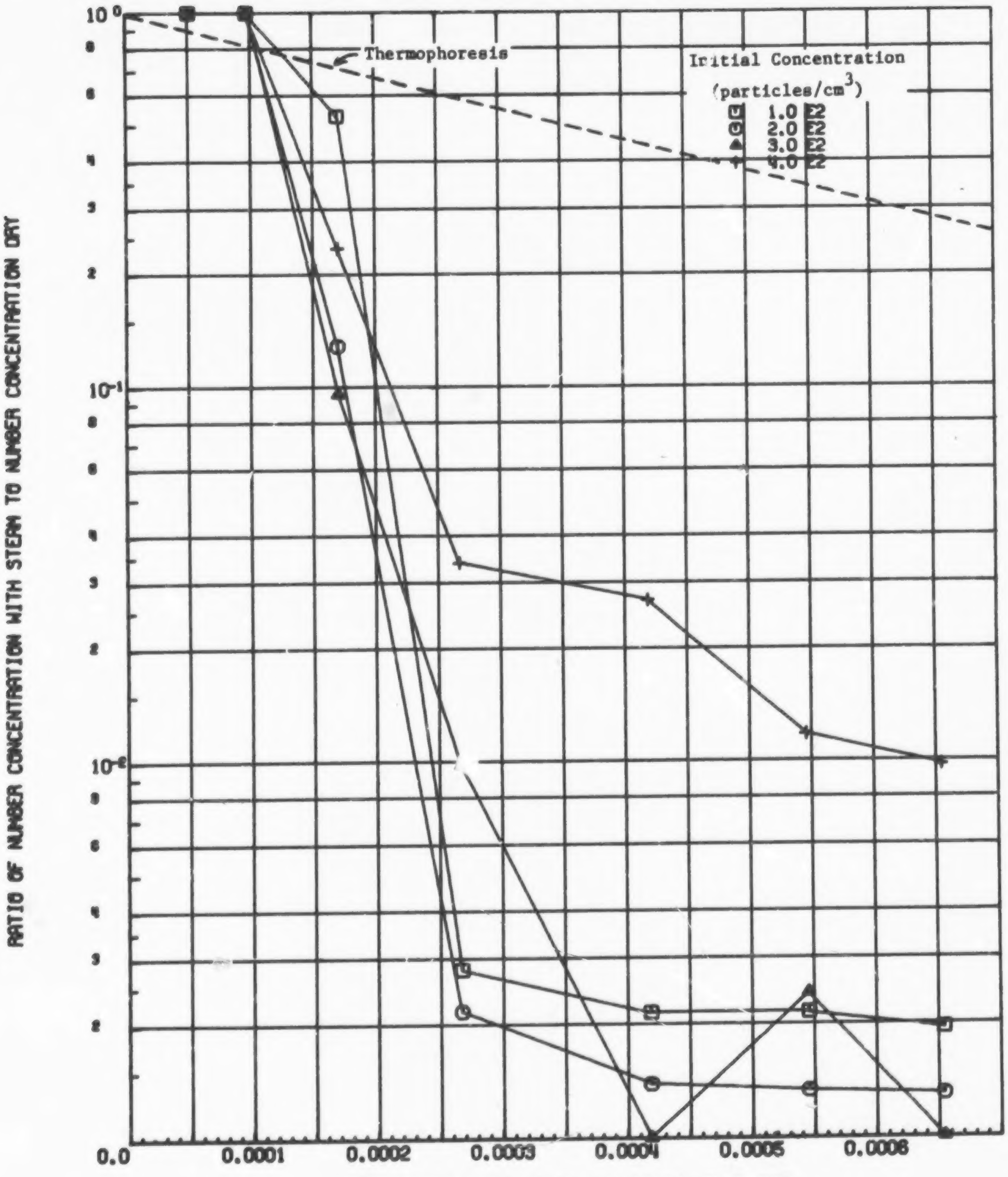


Figure 87. Latex, 1.1 Micron Mass Median Diameter

ORNL-DWG 70-8476

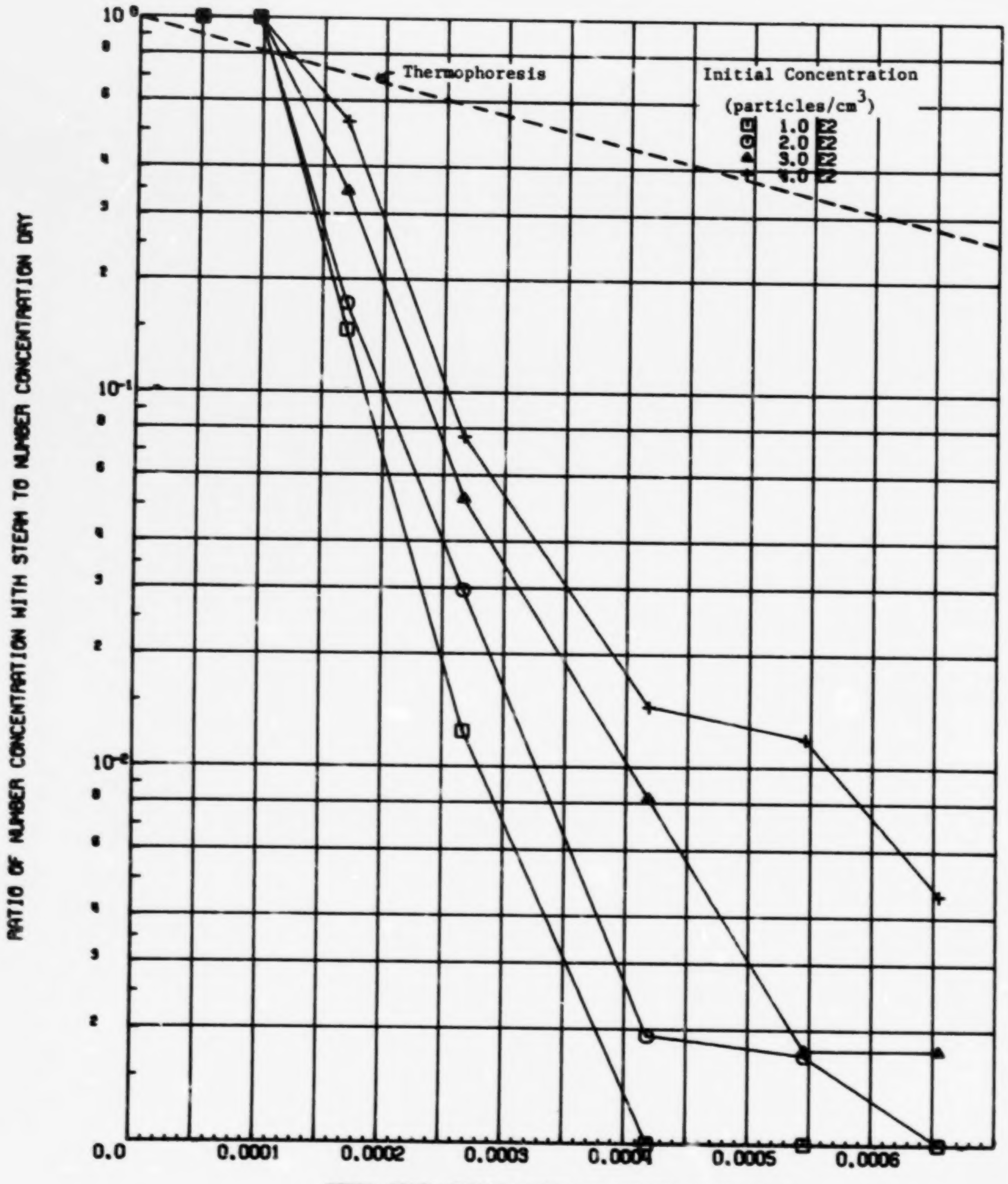


Figure 88. Latex, 0.5 Micron Mass Median Diameter

ORNL-DWG 70-8472

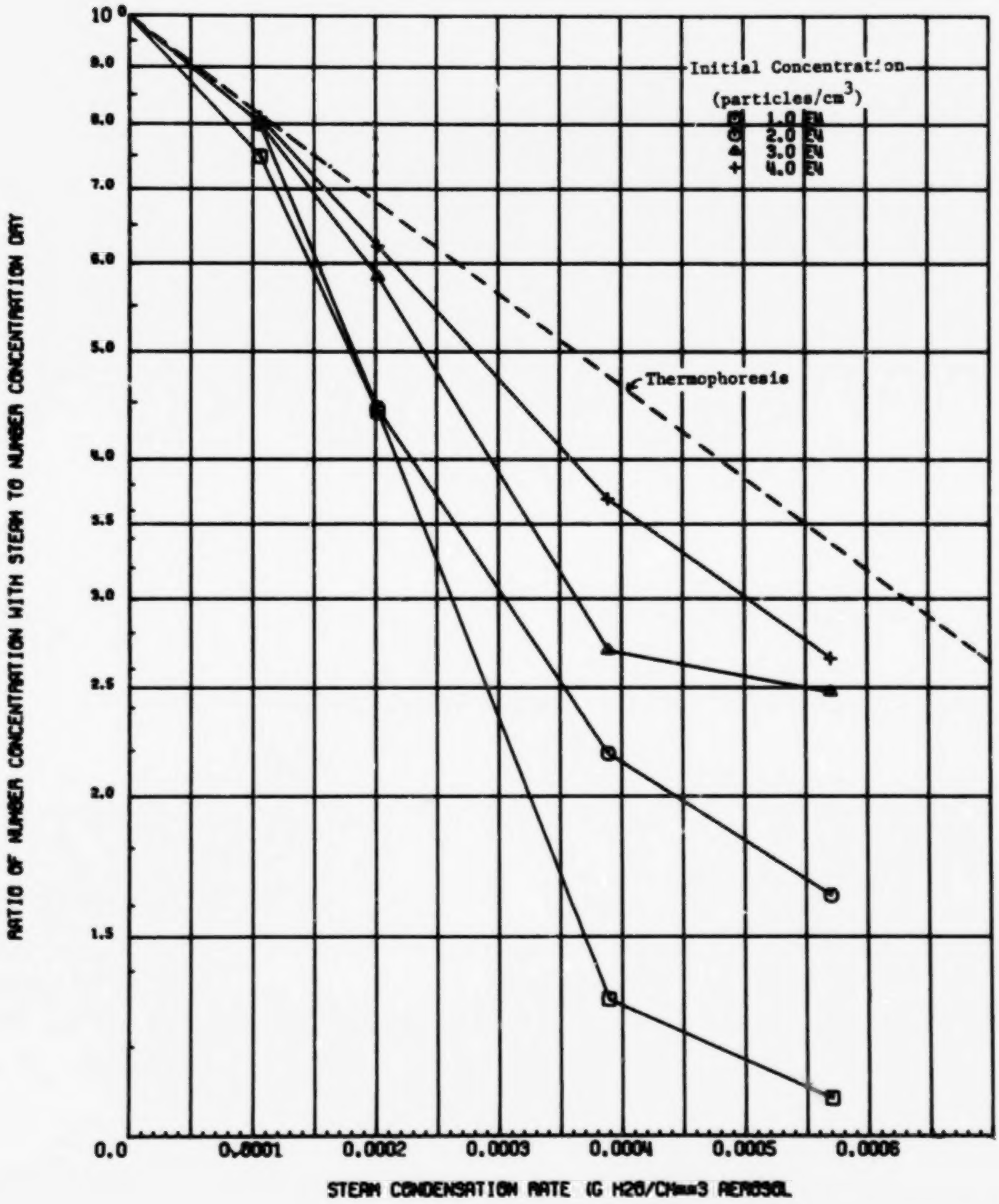


Figure 89. Dioctylphthalate, 0.5 Micron Mass Median Diameter

ORNL-DWG 70-8471

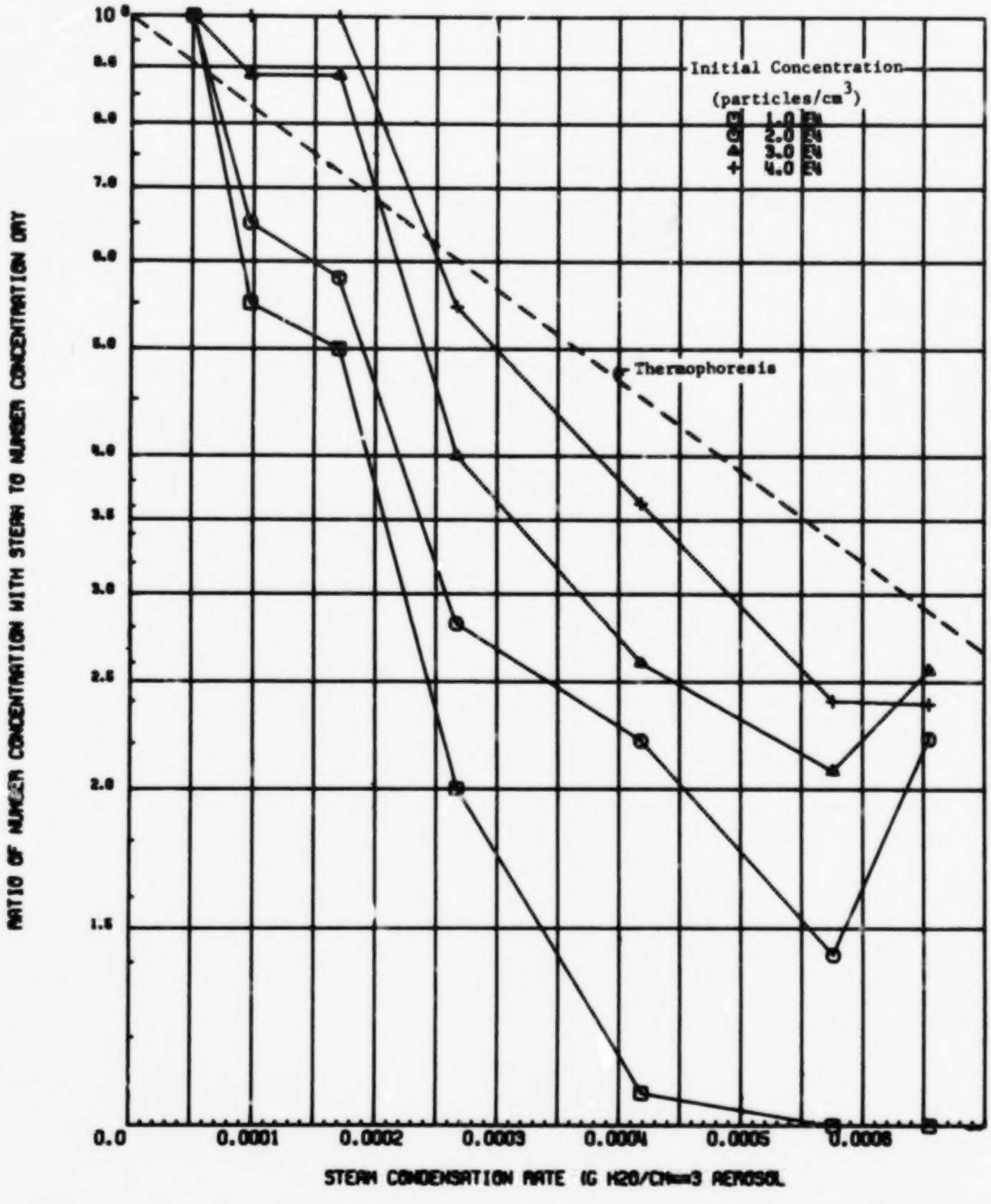


Figure 90. Dioctylphthalate, 0.2 Micron Mass Median Diameter

ORNL-DWG 70-8467

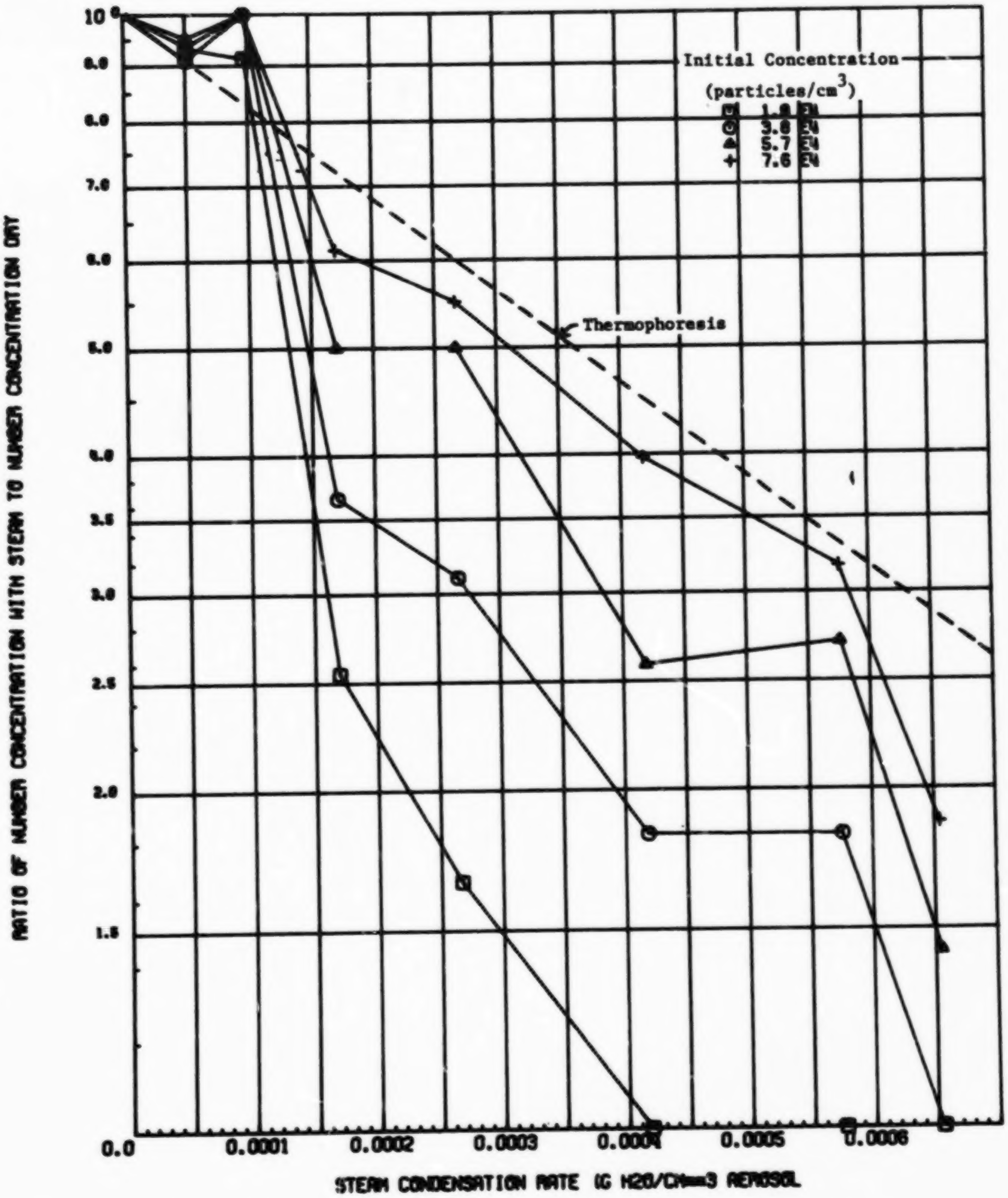


Figure 91. Dioctylphthalate, 0.1 Micron Mass Median Diameter

ORNL-DWG 70-8470

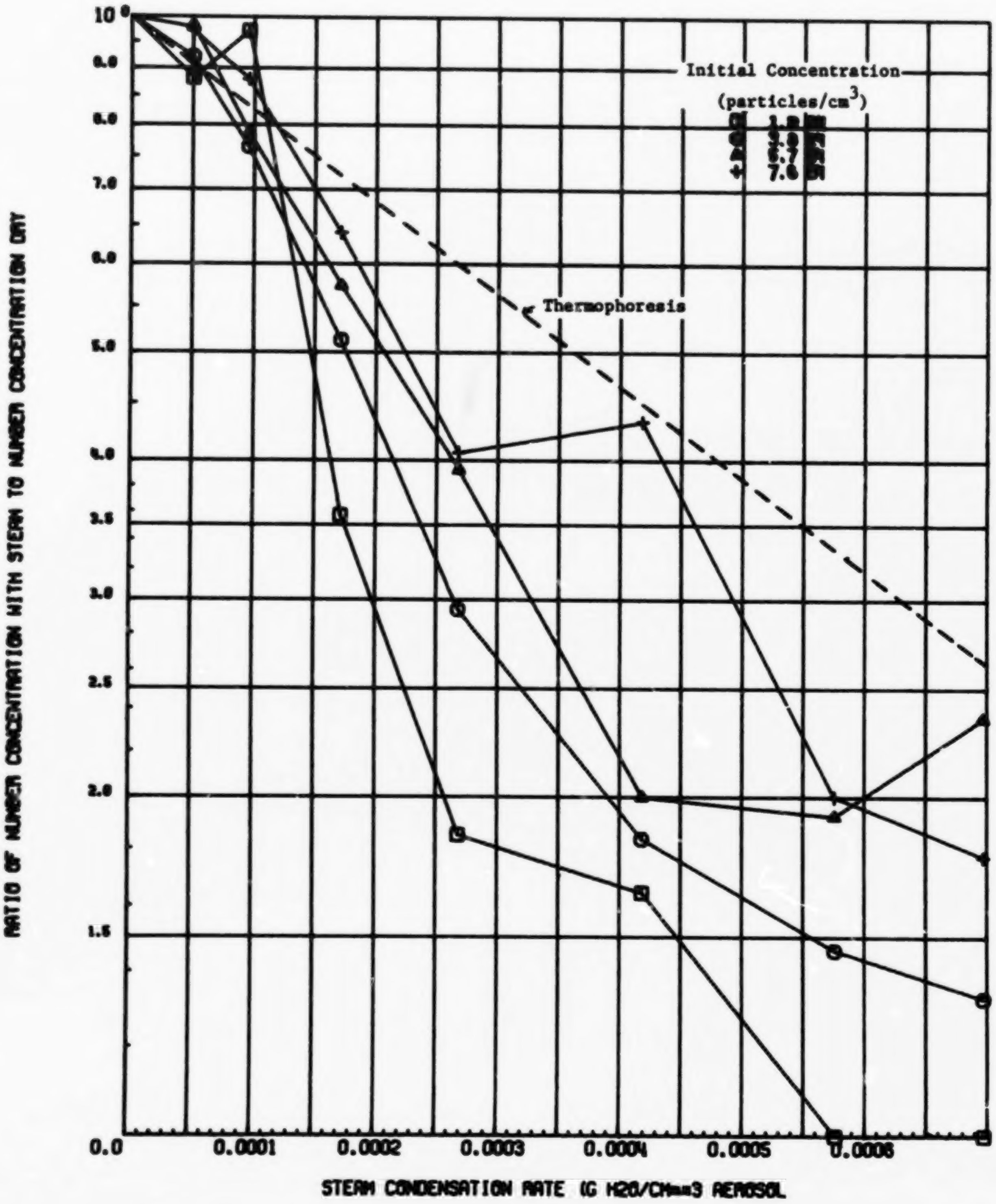


Figure 92. Dioctylphthalate, 0.05 Micron Mass Median Diameter

ORNL-DWG 70-8477

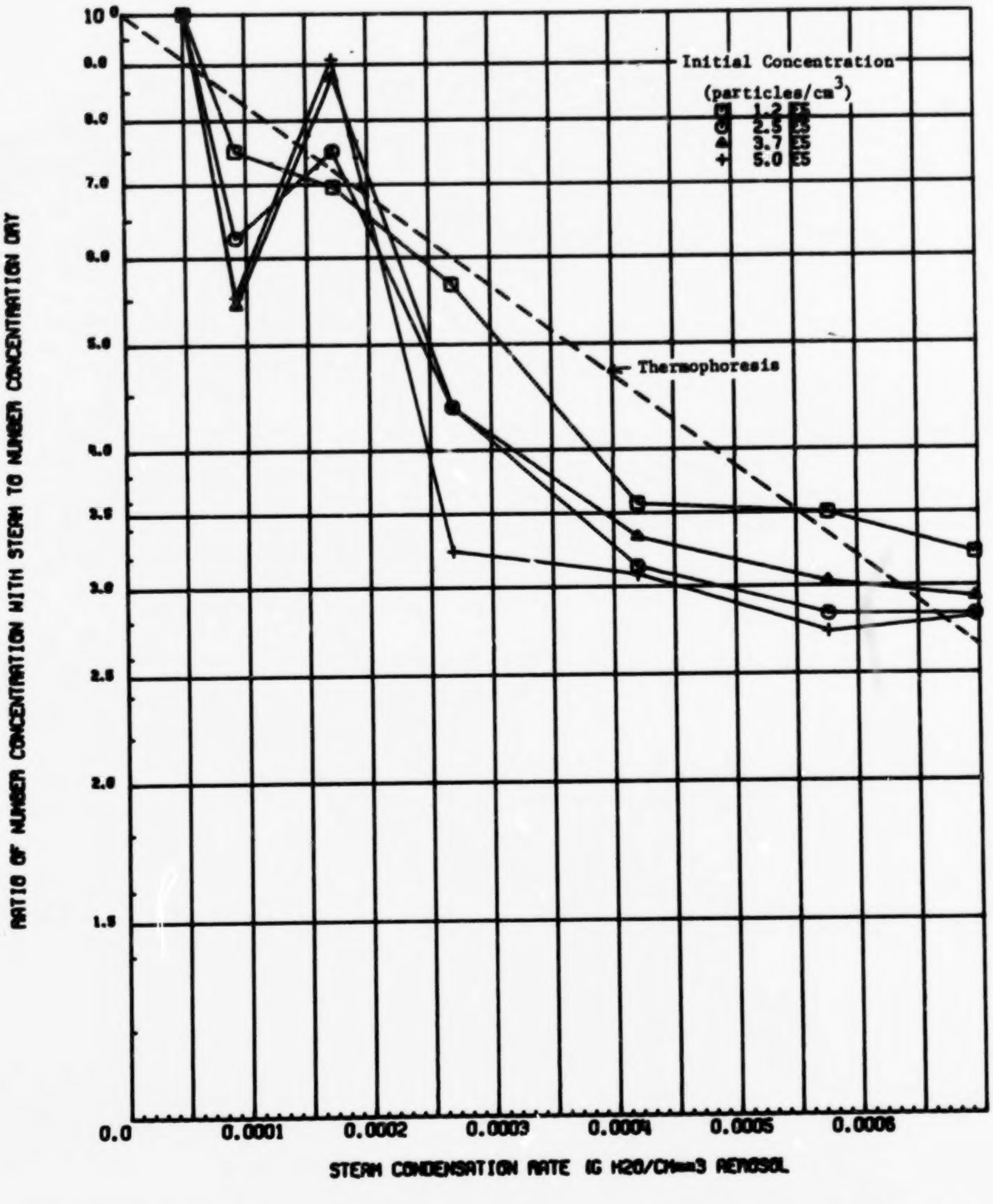


Figure 93. Stainless Steel Oxide, 0.007-15 Micron Diameter

ORNL-DWG 70-8466

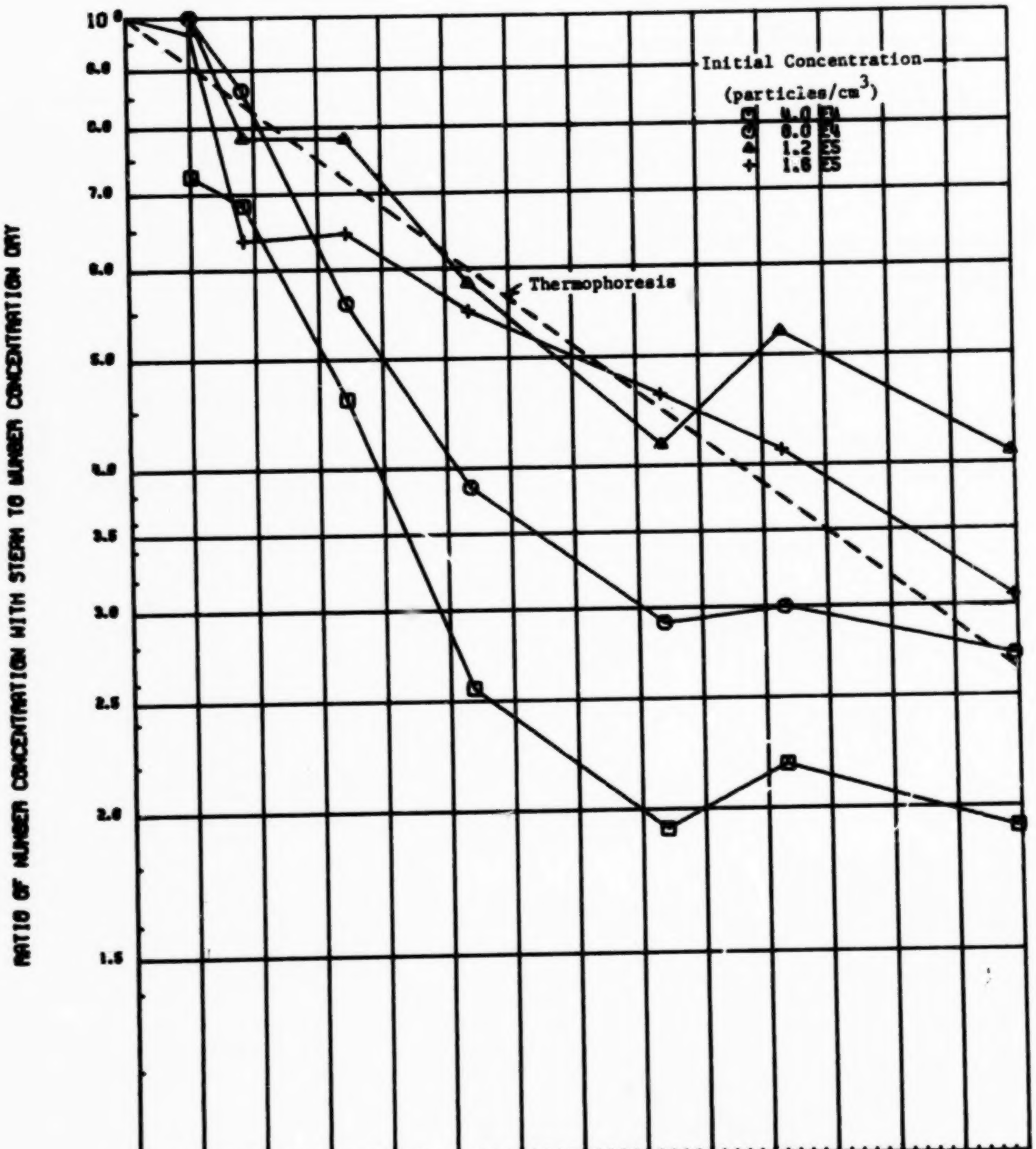


Figure 94. Stainless Steel Oxide, 0.015-6 Micron Diameter

ORNL-DWG 70-8473

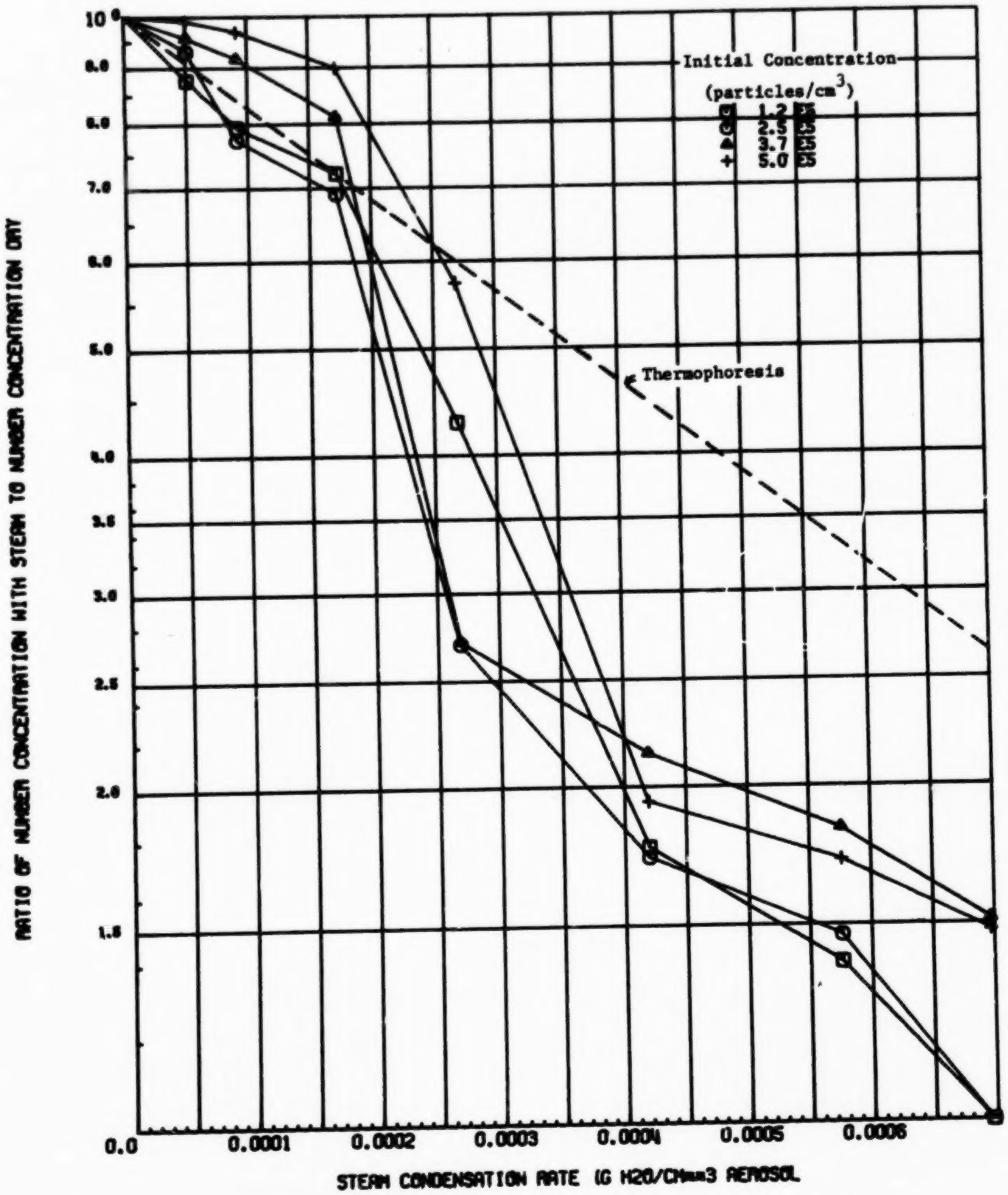


Figure 95. Iron Oxide, 0.015-6 Micron Diameter

ORNL-DWG 70-8474

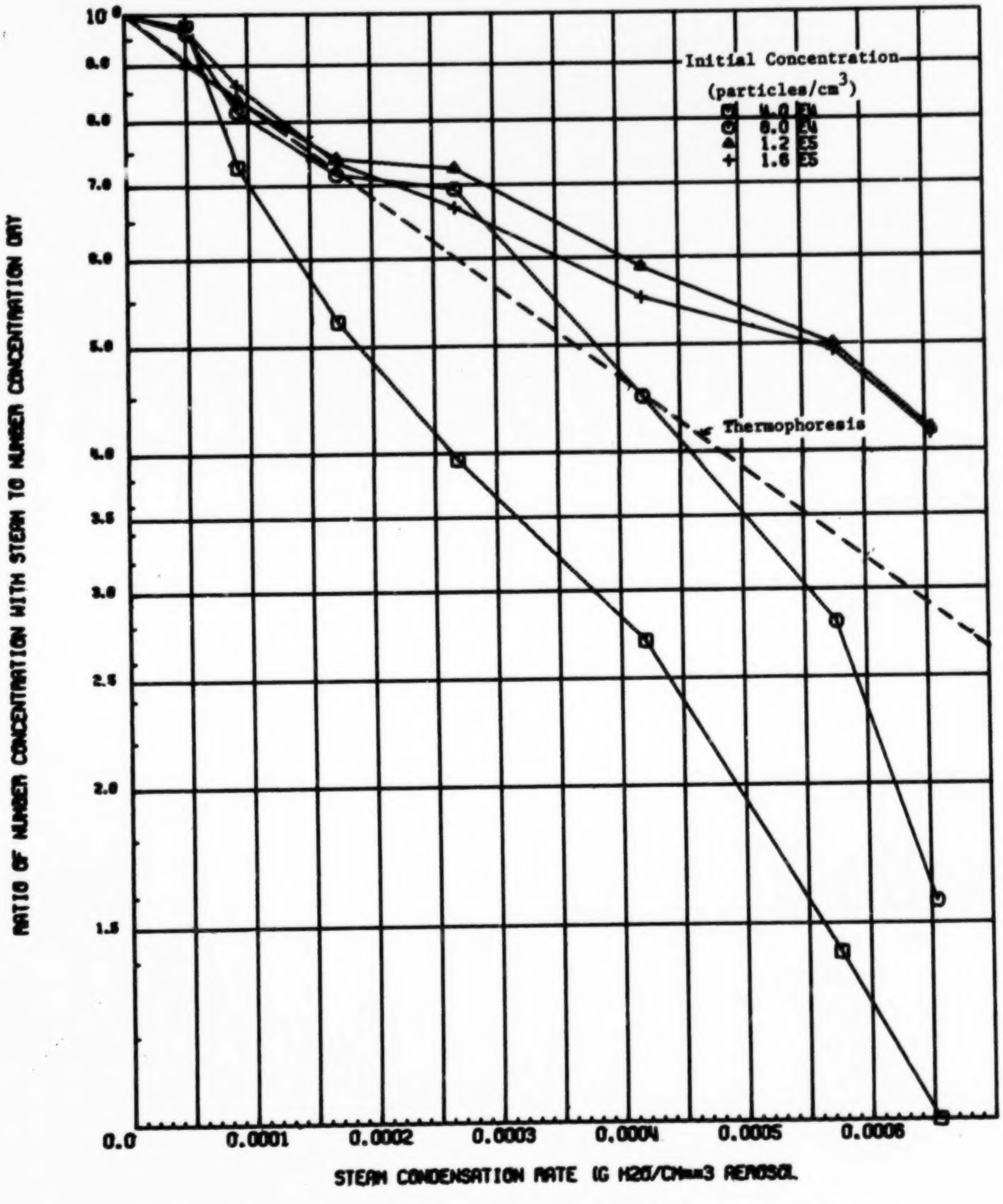


Figure 96. Chromium Oxide, 0.012-7 Micron Diameter

ORNL-DWG 70-8468

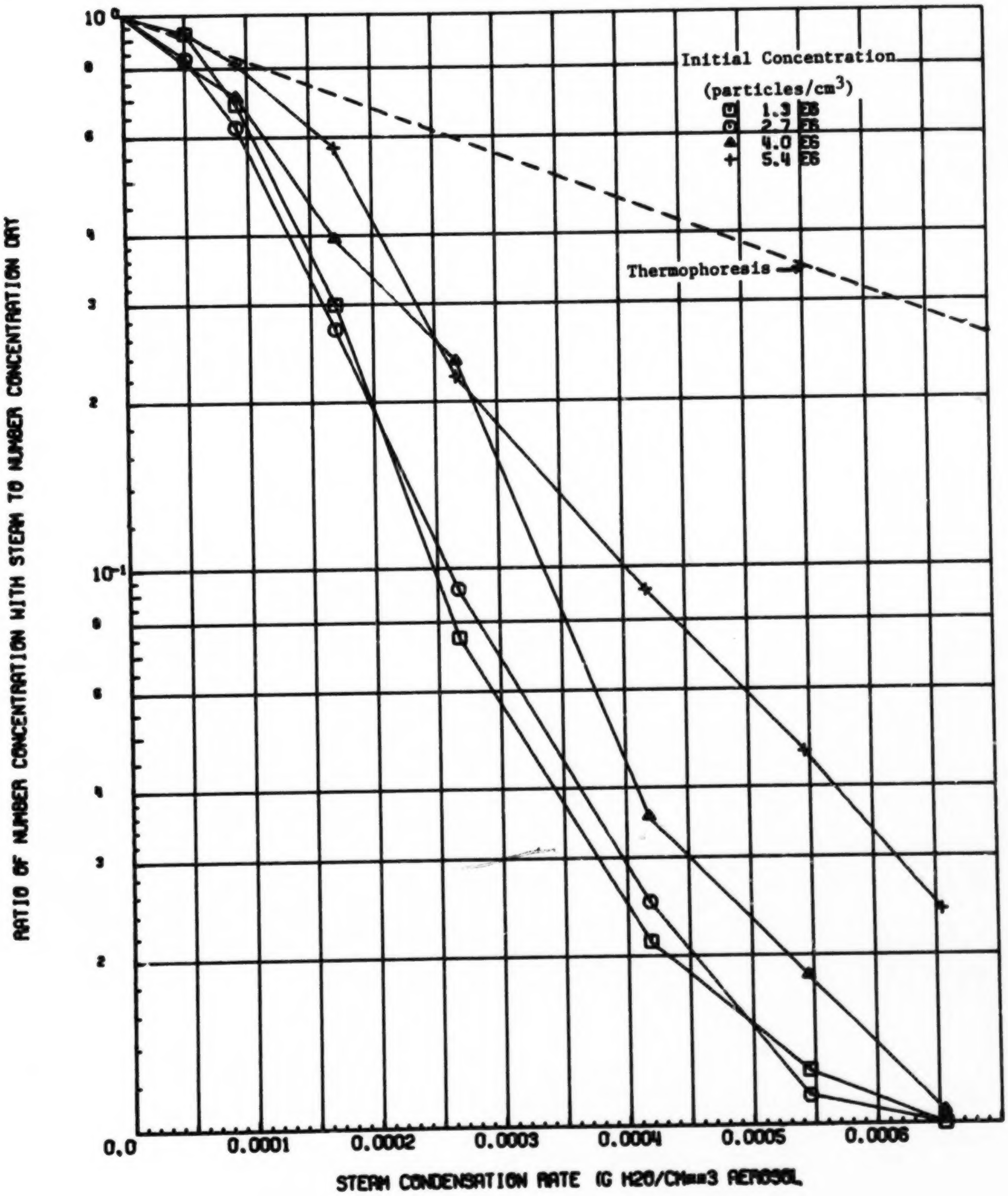
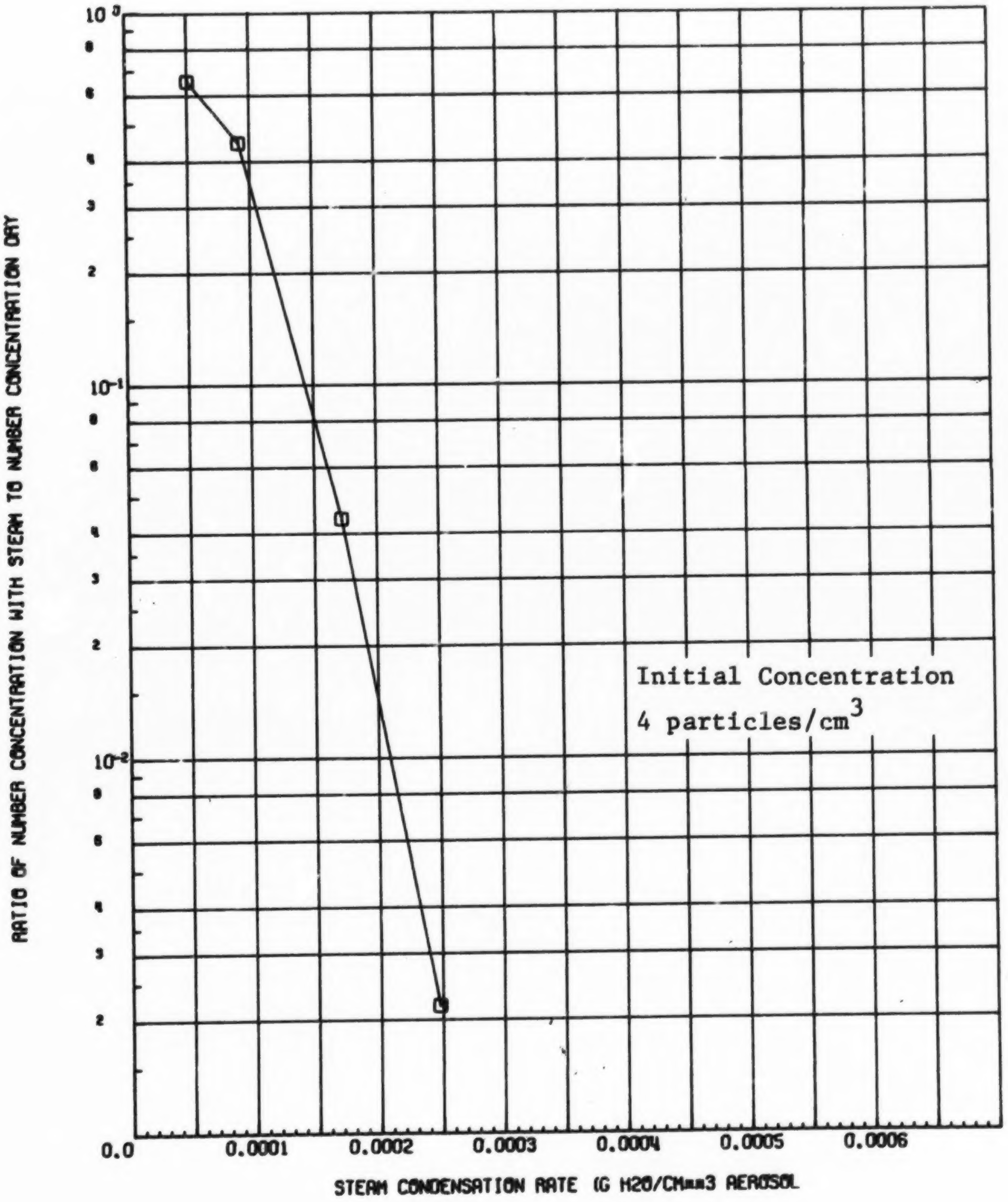


Figure 97. Ammonium Chloride, 0.06-13 Micron Diameter

ORNL-DWG 70-10327



Initial Concentration
4 particles/cm^3

Figure 98. Methylene Blue, 2 Micron

ORNL-DWG 70-10326

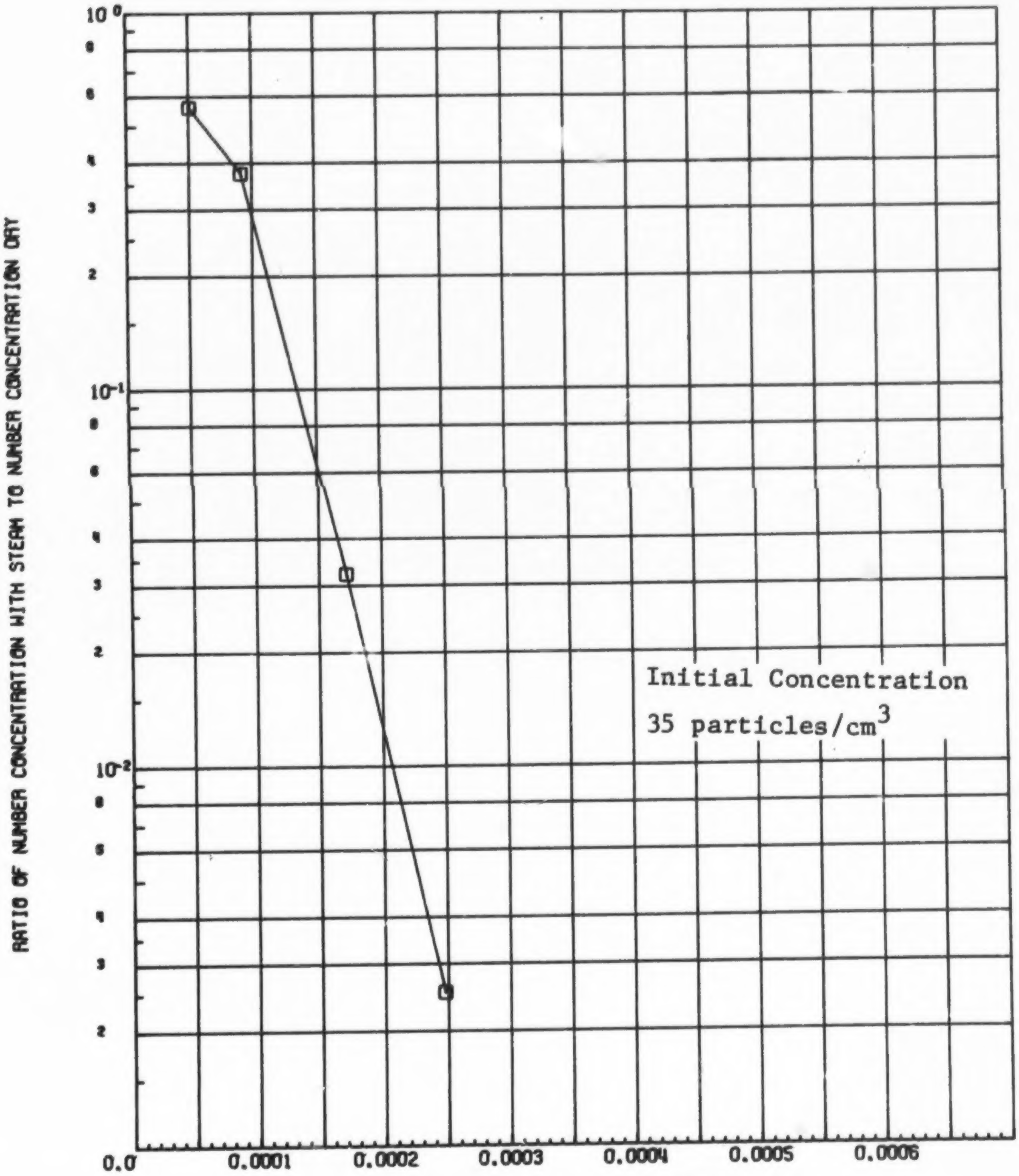


Figure 99. Methylene Blue, 2.7 Micron

ORNL-DWG 70-10325

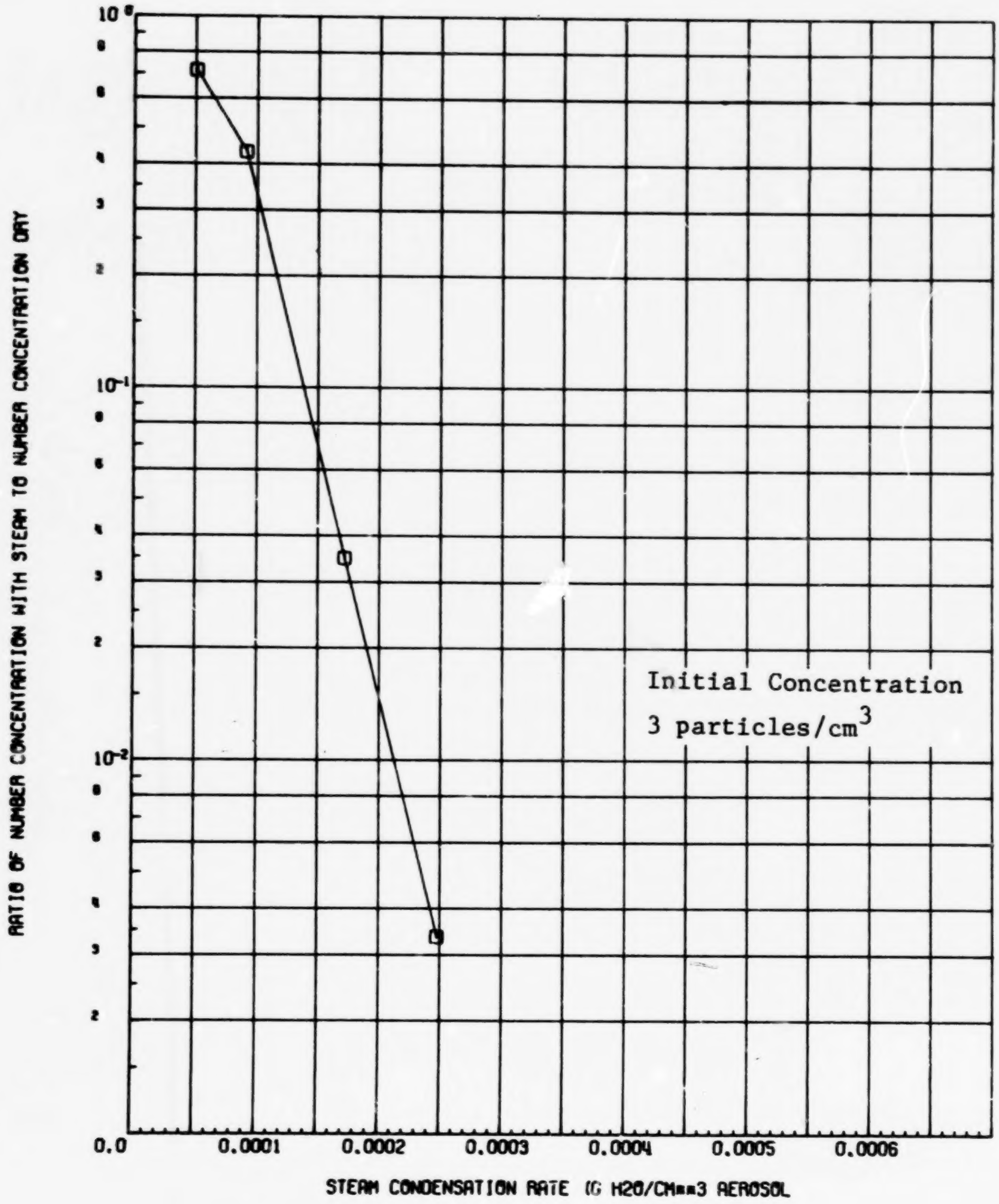


Figure 100. Methylene Blue, 4 Micron

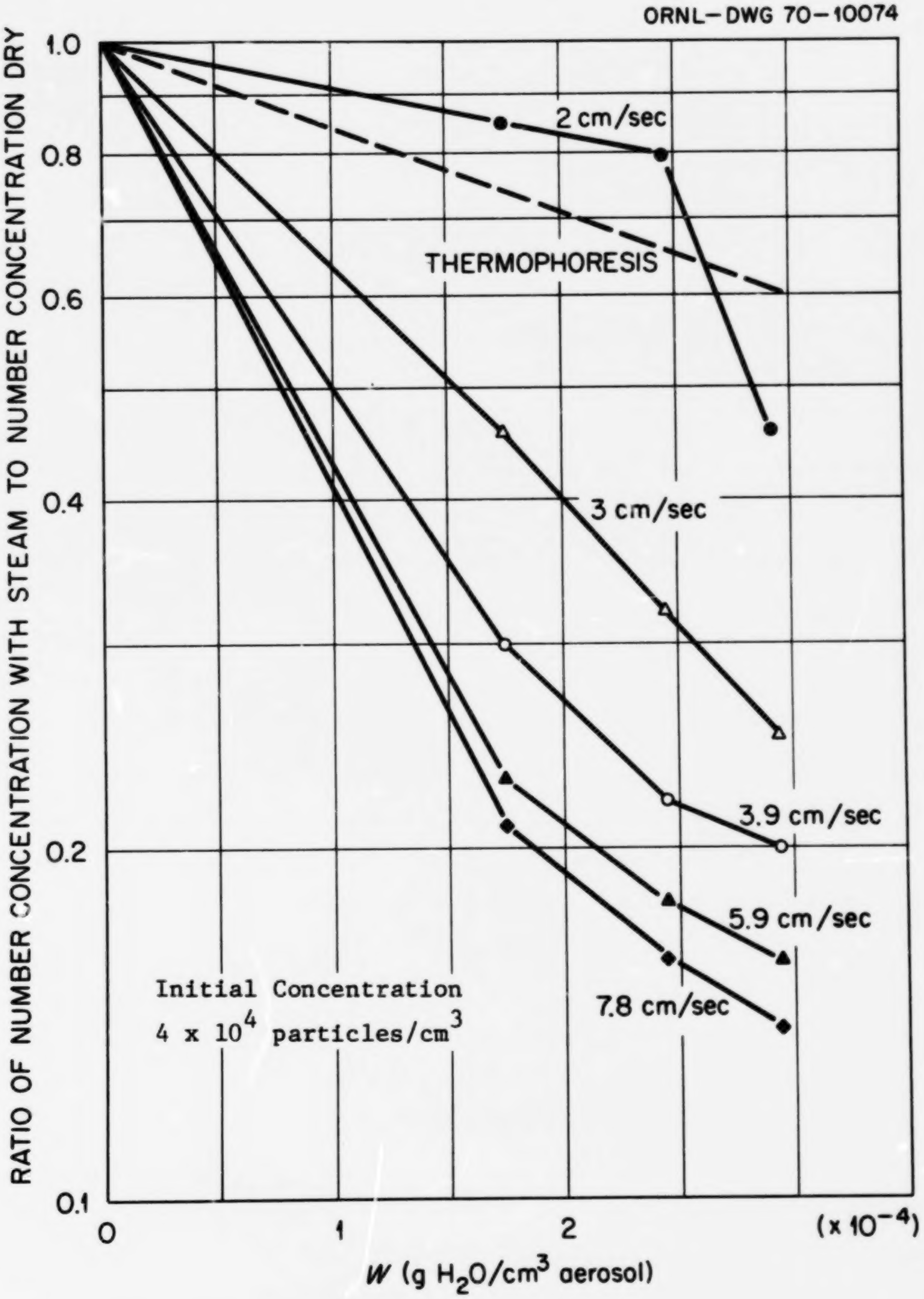


Figure 101. Effect of Velocity, Stainless Steel Oxide Aerosol

VI. Discussions

A. Discussion of the Experimental Results

1. Size Distribution

We will discuss the size distribution ratios (Figs. 35-85) first, then the number concentration ratios (Figs. 86-100) and finally the special experiments to show the effect of velocity (Fig. 101). The first point about the size distribution ratios is that they must be considered as approximate values. The observed particle sizes could be in error as a consequence of variable instrument response to different particle substances, to wet vs dry particles. Wet particles which would have been essentially water droplets may have partially evaporated in the instruments. Other errors due to dilution and sampling could have contributed additional errors. One will notice, for instance, that the distribution ratios were often greater than unity; this is explainable in the larger size ranges; it means that smaller particles grew. However, in the small size end of the spectrum, in some cases, the distribution ratios were still somewhat larger than unity; this may have been due to growth of very tiny nuclei or it may have been an artifact resulting from measurement errors.

The second point is that in many cases particle growth did appear to have occured; (recall that this observation was the major objective). Growth is indicated by a bulge in the distribution ratio values at the higher particle volumes; i.e., growth is indicated by relatively fewer small particles and relatively more large ones. This seems to be apparent with the higher steam condensation rates with latex particles and with all the oxide particles.

The third point is that particle removal in proportion to steam condensation rate is indicated; i.e., in the small size range end of the spectrum where most of the inlet particles were, the distribution ratios decrease (generally) from near unity to lower and lower values as the steam condensation rate increased. This is shown most clearly with the 0.5 micron DOP aerosol; the top curve (i.e., the one with the highest distribution ratios) is for the lowest steam condensation rate; at higher and higher steam condensation rates the ratio values become lower and lower.

The fourth point is that a bulge (i.e., high values) in the distribution ratio plots in the volume range near 10-100 cubic microns occurred with several aerosols. This volume range corresponds to a particle diameter range of about 3-6 microns. This observation is consistent with the way the condenser was predicted to behave. Particles larger than about this range were expected to fall against the updraft in the condenser, therefore reside in the condenser longer, be subjected to the thermophoresis sweep longer and therefore be deposited. Particles smaller than this range (3-6 microns) were generally expected to grow. Hence, this particular size might have been predicted to be (and apparently was) the most likely to penetrate this particular condenser.

A fifth point is also with regard to the bulge (in the 10-100 cubic micron range) in the distribution ratio plot and its significance with regard to the apparent particle growth pattern. We suggested that hydrophobic particles would tend to resist condensation of water and as a consequence a fraction of the particles might undergo massive growth; the rest none. One might expect that all the massively grown particles to deposit in the condenser; the rest would be swept toward the wall by thermophoresis. There would be no grown particles in the effluent, hence no bulge in the distribution ratios (in the 10-100 cbbic micron range or elsewhere). Alternatively, if growth occurs equally on all particles, growth would not be massive; there might well be a tendency for a bulge in the distribution ratios in the 10-100 cubic micron range because the particles all tend to grow toward the 10-100 cubic micron range and if they succeed in getting larger than that they tend to hang in the condenser until they get caught. With these ideas in mind let us look at the results again.

The oxide (hydrophillic) particles generally showed the 10-100 cubic micron bulge; they apparently tend all to grow. The 0.5 micron DOP aerosols quite clearly did not show any bulge. (The other sized DOP particles showed some maxima but generally not in the 10-100 cubic micron range. These cannot be explained at present; one should probably suspect these maxima to be artifacts of unclearly recognized errors.) It is suggested that the DOP particles grew as hydrophobic particles were suspected to grow; i.e., some particles grew a lot, others none.

The latex particles (perhaps the 1.9 micron particles most clearly) appears to have showed a dual behavior. At the lower steam condensation rates there appears to have been to bulge; at the higher steam condensation rates there was a bulge. This apparent behavior is probably an artifact as follows: the latex particle aerosols unavoidably contained a large number of very tiny nuclei of the substance which is put into the latex bead slurry (from which the aerosol is atomized) to help prevent agglomeration of the beads in the slurry. At the higher steam condensation rates these tiny nuclei probably succeeded in growing into the 10-100 cubic micron size range. It appears probable therefore that the latex particles also grew as hydrophobic particles were predicted to grow; some a lot, some none.

The methylene blue particles showed a bulge in the 10-100 cubic micron range at low steam condensation rates. It is likely that at high steam condensation rates (and at the very low number concentrations employed here) that there was enough water so that virtually all the particles grew to be quite large and therefore deposited. It appears that the methylene blue particles grew as hygroscopic particles were expected to; they all grew.

The ammonium chloride showed no tendency for a bulge in the 10-100 cubic micron range; in fact there were virtually no particles in this size range. The special feature of this aerosol (other than the particles being hygroscopic) was the high concentration. This aerosol would have therefore been particularly likely to undergo further growth (subsequent to condensation) due to turbulent agglomeration. That this happened cannot be proved but it is consistent with the data; turbulent agglomeration is especially rapid with larger particles (as described in Section I-D-2) and at high number concentration. In general, the effect would have been that observed, namely a kind of large particle cutoff; all the particles larger than some value (apparently about 1 cubic micron) would agglomerate to a much larger size and deposit. So the ammonium chloride particle data is consistent with the growth pattern suggested for hygroscopic particles, namely that they all grow.

So generally the size distribution ratio results suggest (or are consistent with the idea) that the hygroscopic and hydrophillic particles (i.e., ammonium chloride, methylene blue and the metal oxides) all grew more or less uniformly by condensation. The hydrophobic (latex and DOP) particles underwent another growth pattern; a fraction grew massively, the others did not grow.

2. Number Concentrations

We need now to consider the number concentration ratio results (Figs. 86-101). The first point of interest is a direct consideration of the economy of the energy used to remove particles. In the (approximately) best case, say for ammonium chloride particles we achieved 90% removal with about 2.5×10^{-4} g/cm^3. This corresponds to 3.4×10^3 hp/1000 ft^3/min.

It is now convenient to discuss the hydrophobic (latex and DOP) particle results first then the hydrophillic and hygroscopic particle results. In brief, the relationships expressed in Eqs. (60) and (62) and demonstrated on Fig. 17 describe the latex and DOP results quite adequately and in terms of an approximate theory(described earlier, IV-B). The approximate theory includes two partially defined constants; i.e., K which has a value of 3×10^3 cm^3 aerosol/g H_2O and K" which has a value of 4×10^7 particles/g H_2O. These constants might be dependent on the nature of the particle substance and the water vapor supersaturation. One readily apparent outcome of the relationship suggested in Fig. 17 is that at high number concentration (i.e., N_o greater than 10^4) removal efficiency increases (i.e., N/N_o decreases for a given steam condensation rate) as the inlet number concentration, N_o decreases. This is indeed readily apparent with the DOP aerosols with number concentration of 2-8 x 10^4 particles/cm^3. At lower number concentration the removal efficiency is not dependent on inlet concentration; this is approximately true, especially for the 1.1 and 0.5 micron latex aerosols.

The interpretation of the number concentration ratio results for the hygroscopic-hydrophillic particles is a little more complete. The predictions are in terms of a constant K' which (if no turbulent agglomeration occurs) is the fraction of the steam which condenses on particles. If K' is greater than unity it was presumed to suggest that turbulent growth had occurred. These predicted N/N_o values were shown on Fig. 16.

The obvious thing to do is estimate values of K' for each aerosol. This was done on a very approximate basis (because the fit of the data to the predicted curves does not allow otherwise). These estimates are listed below:

Aerosol	K'
Stainless steel oxide (0.007-15 micron)	1
Stainless steel oxide (0.015-6 micron)	1
Iron oxide	10
Chromium oxide	1
Ammonium chloride	100
Methylene blue	10^{-3}

These values appear to be reasonable as follows. The methylene blue aerosols were very dilute; presumably many of the water molecules therefore found the cold wall before finding a particle. Hence K' was a low value. With the stainless steel and chromium oxide aerosols K' was about unity which suggests that the water mostly condensed on the particles and little turbulent agglomeration occurred which was according to the experiment design. The iron-oxide particles, with K' about 10 appeared to have undergone some turbulent agglomeration. This is not too unreasonable since the number concentrations were quite high (1-5 x 10^5 particles/cm^3). However, the 0.007-15 micron diameter stainless steel oxide aerosol at similar concentration did not show the same effect. There is a minor unexplained comparison here. Finally the ammonium chloride aerosol results suggested a K' of 100; this suggests that turbulent growth occurred which is consistent with the distribution ratio results (above) and the very high number concentration (1-5 x 10^6 particles/cm^3).

3. The Effect of Velocity

The special tests with stainless steel oxide aerosols which were done to demonstrate the strong effect of velocity (Fig. 101) can also be partially interpreted on the basis of K' (as above). The approximate values of K' (from the results on Fig. 102) are:

Velocity	Re	K'
2.0	130	3
3.0	200	4
3.9	250	6
5.9	390	11
7.8	510	17

The correlation in the table is consistent with the idea that the higher the velocity, the more agglomeration, the higher the value of K'. It was considered not appropriate to try to proceed further with these data; we are not sufficiently confident of them. They do serve to demonstrate that velocity (hence probably turbulence) is important. It is also notable that the removable efficiencies which we obtained were considerably less, for a given velocity, than Goldsmith obtained (and as shown on Fig. 14). This was predicted (as noted earlier); he probably impacted significant numbers of particles in an elbow at the outlet of the condenser.

B. Discussion of the Observed Cost of Particle Removal Using Steam Condensation

The ultimate purpose of this work is, of course, to help develop an inexpensive means of removing fine particulate matter from gas streams. It is important therefore to consider the cost of condensing steam in comparison to the benefit from it.

The experimental data were presented in Figures 86-101 as semi-log plots of the ratio of the number concentration after steam condensation to the number concentration dry vs the steam condensation rate in units of grams of water condensed per cm^3 of aerosol. The values of steam condensation rate varied from zero to 0.0007 g/cm^3. At 0.0007 g H_2O/cm^3 steam condensation rate, the particle removal efficiencies usually varied with particle concentration and other factors as described above, but were often about 90% and was about 99% for NH_4Cl. In a special series of tests (Fig. 101) with higher velocities and with stainless steel oxide particles (where we expect that additional particle growth and consequent removal occurred due to turbulence) we achieved almost 90% removal with 0.0003g of water condensed per cm^3 of aerosol.

In other words, we commonly achieved high removal efficiencies with 0.0007g H_2O/cm^3 aerosol and in a particular test series we achieved high efficiencies with 0.0003g H_2O/cm^3.

0.0007g of water per cm^3 of aerosol is equivalent to 10^3 hp/$10^3 ft^3$/min or to 44 lbs of steam per 1000 ft^3 of aerosol or to 4.6×10^4 Btu/1000 ft^3. 0.0003g/cm^3 is equivalent to 290 hp/$10^3 ft^3$/min or to 19 lbs/1000 ft^3 or to 2×10^4 Btu/1000 ft^3. Assuming that steam costs \$0.25/10^6 Btu[41] it follows that we commonly achieved high removal efficiencies at a cost of

\$0.011/10^{3}ft^3 (i.e., \$0.011/10^{3}ft^3 corresponds to 0.0007g (cm^3). We achieved high efficiencies in the high velocity series with \$0.0047/10^{3}ft^3.

We can compare these costs with those using inertial devices (which do not remove the little particles but none the less provide a cost target). From reported[17] correlations (see Fig. 11) we know that many inertial devices use up to 10 hp/10^{3}ft^3/min. 10 hp/10^{3}ft^3/min is equivalent to 0.12 kilowatt hours/10^{3}ft^3. Assuming that electric power costs \$0.01/kilowatt hour, then it follows that common inertial devices consume \$0.0012/10^{3}ft^3 to remove fine particles (inefficiently) from air streams.

So our simple laboratory experiment (assuming that steam costs \$0.25/10^{6}Btu and that electric power costs \$0.01/kilowatt hour), commonly achieved high removal efficiencies with fine particles for \$0.011/10^{3}ft^3 and in some cases for \$0.0047/10^{3}ft^3 whereas common inertial devices inefficiently remove fine particles at a cost of about \$0.0012/10^{3}ft^3. In other words, our experimental device achieved a cost efficiency of the same order of magnitude as operating inertial devices.

It should be emphasized that our experimental device was not designed to achieve high removal efficiencies but rather to demonstrate particle growth in condensing steam. In other words, one would expect to do better than we have done.

VII. Conclusions

A. Pertaining to Particle Growth

The major object was to determine if particles of several sizes, substances and concentrations would undergo growth in steam at low water vapor supersaturations. Growth did occur in all cases. This was most clearly shown by the number concentration ratio plots (Figs. 86-100); the deposition behavior was clearly that predicted with thermophoresis as the deposition mechanism aided by the longer residence time caused by particle growth. The size distribution results, although less certain, tended either directly or indirectly to confirm that particle growth occurred.

We wished also to deduce what we could about the mechanisms of particle growth including any dependences on particle substance, size or concentration. Such deductions were made with regard to mechanisms of growth; a simple model for growth of hydrophobic particles and a second model for growth of hydrophillic or hygroscopic particles were suggested which explain the observed results approximately. The bases of the models are that a population of hydrophillic or hygroscopic particles all grow in water vapor at low supersaturation; with a population of hydrophobic particles a fraction undergo massive growth, the rest no growth. These models predict a substance effect (hydrophobic vs hydrophillic or hygroscopic); they include no particle size effect (and the data did likewise); they predict the (observed) particle concentration effect. These predictions of the models insofar as the condenser experiment is concerned (at a velocity of 3.8 cm/sec) are shown on Figs. 16 and 17.

A special series of experiments demonstrated that the removal efficiency of the condenser experiment sharply increased with velocity. This qualitatively confirms the prediction that turbulence (or velocity gradients in laminar flow) causes further growth (which was shown in turn to increase removal efficiency).

B. Pertaining to the Economics of Particle Removal

We wished to deduce as much as possible about the potential economy of steam condensation scrubbing. We considered the question of economy both from a theoretical basis and from the basis of the observed results. By means of arguments based on information in the literature it was determined (Section II-D) that thermophoresis is more efficient as a deposition mechanism (in terms of energy consumption) than diffusiophoresis. It was also determined that thermophoresis is considerably less efficient than centrifugation or electrostatic precipitations. It follows then, that the direct deposition mechanisms associated with condensing steam (i.e., thermophoresis and diffusiophoresis) are probably not economically useful, but that steam condensation scrubbing might be applicable in removing fine particles and would have to rely on particle growth in steam perhaps followed by growth via turbulent agglomeration and finally by relatively cheap removal of the grown particles with an inertial device (such as a cyclone).

More specifically, it was indicated (with information in the literature in Section II-D) that the energy required to produce enough steam to grow 10^5 particles/cm^3 up to 2 micron radius drops of water would be about 4.6 hp/1000 (cu ft/min). The 2 micron radius drops could then be separated in a cyclonic device. Alternatively, one might grow the particles by condensation to 1 micron in radius which would require about 0.6 hp/1000 (cu ft/min) and then (it was estimated) grow them further to about 9 microns radius by turbulent coagulation with 1 hp/1000 (cu ft/min) for a total power consumption of 1.6 $hp/10^3ft^3/min$. The 9 micron drops would be very easily spun out.

These power requirements are in the range (i.e., 1-10 hp/1000 cu ft) used in inertial devices. In other words, it is suggested with approximate theory that even if the steam employed was produced with electric power (such as used to power inertial devices) that a steam condensation scrubber would be economically competitive. If steam is assumed to cost $\$0.25/10^6$ Btu and electric power $0.01/kwh then the 1-10 $hp/10^3ft/min$ as electric power for an inertial device would cost $0.00012 to $0.0012 per 10^3ft^3 and the 1.6-4.6 $hp/10^3ft^3/min$ as steam for a condensation scrubber would cost 2×10^{-5} to 6×10^{-5} $\$/10^3ft^3$.

These power estimates do not allow for any wasted steam but on the other hand, it is likely that in any actual device other growth and deposition mechanisms would aid in the removal. It is therefore not really clear whether the predictions are conservative or liberal.

From the point of view of the observed results the following are true. We commonly observed (as explained in Section VI-B) greater than 90% removal efficiency with 0.0007g H_2O condensed per cm^3 of aerosol and in one series of tests at higher velocity (hence with more particle growth due to turbulence) high efficiencies were observed at 0.0003g H_2O/cm^3. These steam condensation rates correspond (on the basis of the power equivalent to the heat required to generate the steam) to 10^3 and 290 $hp/10^3ft^3/min$, respectively. But the cost of this power as steam (at $\$0.25/10^6$ Btu) would be $0.011 and $0.0047 per 10^3ft^3, respectively.

So in summary inertial devices consume about 1.2×10^{-4} to 1.2×10^{-3} $\$/10^3ft^3$ of treated gas volume. Approximate theory indicated that steam condensation with optimum use of growth by turbulent agglomeration could be used to treat polluted gas streams for 2×10^{-5} to 6×10^{-5} $\$/10^3ft^3$. The experimental system (Fig. 15) achieved high removal efficiencies with a power consumption of 1.1×10^{-2}-4.7×10^{-3} $\$/10^3ft^3$.

C. Pertaining to Removal Efficiencies

Neither the experimental results nor the approximate theory (in Section II-D) provide us with a quantitative estimation of possible removal efficiencies or estimates of costs vs efficiencies that might be possible. We can make qualitative predictions based on theory; the results in hand demonstrate that high (>90%) removal efficiencies can be obtained and we expect that additional work would establish quantitative relations between removal efficiencies, costs, particle sizes and particle substances. We will note here the qualitative predictions; suggestions for future work appear in Section VIII below.

We have predicted (in Section II-D) that a useful particle removal process would involve: first particle growth by condensation of water, second growth by turbulent agglomeration and third removal by inertial impaction. The removal efficiency would depend on: (1) what fraction of particles underwent growth by condensation of water and (2) the efficiency of the inertial impaction device. The efficiency of impaction devices is quite well known; we will consider what fraction of particles would be expected to grow.

The simple model for hydrophobic particles presumed that a fraction of the particles allowed water to condense on them and hence grew. The simple model for hydrophillic and hygroscopic particles (Section II-D-2) presumed that all particles grew equally. It is probable that these models represent the extreme possibilities and that real systems will behave somewhere between these extremes. The two parameters that are predicted to determine the fraction of the particles which grow, are the tendency for the particle surfaces to adsorb or absorb water (i.e., the hydrophobic, hydrophillic or hygroscopic nature of the particle substance) and the water vapor supersaturation at the instant of the beginning of growth by condensation. There would also be a third parameter, namely the particle size before growth by condensation; this third parameter would probably be less important than the other two.

To sum up, we would predict that the removal efficiencies would be intrinsically higher for hygroscopic particles than for hydrophillic particles than for hydrophobic particles. We would predict that with a mixture of particle substances the more hydroscopic or hydrophillic would tend to be removed; the more hydrophobic would tend to remain. We would predict that the efficiency would be increased by increasing the water vapor supersaturation.

VII. Suggestions for Future Work

A. Additional Experiments of the Kind Presented Above

There should be both more laboratory work and pilot plant work done. We will only consider suggestions for future laboratory work here.

We suggest that more experiments of the kind reported above should be done. The objectives would be to demonstrate the effect of particle number concentration over a wide range (perhaps 10^2 to 10^6 particles per cm^3), and to demonstrate more accurately the effects of particle size and substance.

The data in hand indicate that the number concentration is very important. The data and their interpretation infer that at relatively low number concentrations (perhaps up to about 10^4 particles/cm^3) the removal efficiency improves as the concentration decreases, i.e., as the amount of water available per particle increases. Some of the data and their interpretation infer that at very high concentrations the other growth process, i.e., turbulent agglomeration became important and in this regime removal efficiency increases with number concentration, (because the rate of turbulent growth increases with number concentration). We suggest that these observed effects and postulated causes be studied by a series of experiments which cover a very wide range of number concentrations (perhaps 10^2-10^6 particles/cm^3). Such a series should be done (probably for a wide size distribution aerosol) for each class of substance, i.e., for a hydrophobic aerosol (probably DOP) for a hydrophillic aerosol (probably stainless steel oxide) and for a hygroscopic aerosol (probably ammonium chloride).

The data in hand show that the number concentration effect is so important that one needs to control it rather well in order to observe effects of particle size and substance. We therefore should do more tests at a few chosen number concentrations in which the particle size (or narrow size distribution aerosols) and class of substance (i.e., hydrophobic, hydrophillic or hygroscopic) are varied one by one.

Of course, the additional tests should be planned around the existing data to minimize the amount of additional work.

B. Experiments to Demonstrate the Effects of Turbulence and Super-Saturation

We anticipate that the eventual device would have a cost efficiency dependent on optimization of particle growth by condensation and by turbulent agglomeration. It is cheaper to grow the very tiny nuclei a little bit by condensation but it is cheaper to carry on the growth of larger particles by turbulence. The special experiments (vs velocity) in the present study showed that indeed turbulence (or a velocity gradient in laminar flow) did increase the removal efficiency so we know the anticipated effect is real. A systematic study of turbulent agglomeration needs to be done to enable quantitative optimization of the two particle growth mechanisms.

We also anticipate that the removal efficiency of a steam condensation scrubber system will depend on the supersaturation (and the tendency for the particle to adsorb water). This effect also needs to be quantified, i.e., the probability that a particle will grow needs to be quantitatively related to supersaturation as well as particle size and substance.

Details of possible experiments to accomplish these two things are beyond the scope of the present report.

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